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CORN AND SOYBEAN BIODIESEL BLENDS AS ALTERNATIVE FUELS FOR DIESEL ENGINES

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ABSTRACT

An experimental study has been carried out for investigating effect of corn and soybean biodiesel blends (C20 and S20) with diesel fuel on performance of diesel engine. Tests are conducted with different engine speeds, loads and IP of 180, 190 and 200 bar. A/F, m_f, T_{exh}, T_{wall}, P_{cyl} and position of maximum pressure are studied. For high engine speeds, loads and IP, mass of fuel injected, BP, η_{Bth}, η_V, T_{Wall} and P_{cyl} for S20 are higher than for diesel fuel while A/F ratio, BSCF and T_{exh} for S20 are lower than for diesel fuel. For 190 bar as IP, P_{max} for C20 is higher than for diesel fuel and S20. With 200 bar as IP, P_{max} for diesel fuel is higher than for C20 and S20 due to low viscosity, good mixing and high heating value. Position of P_{max} attains within 14-18 CA deg ATDC for all fuels.

KEY WORDS

diesel engine, biodiesel fuel, performance, cylinder pressure.

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NOMENCLATURE

ATDC	After top dead center.
A/F	Air/ fuel mass ratio, kg of air/kg of fuel.
BTDC	Before top dead center.
BSFC	Brake specific fuel consumption, kg/kW h.
BP	Brake power, kW.
CA	Crank angle, deg.
CIE	Compression ignition engine.
CO	Carbon monoxide, %.
CN	Cetane number.
C	Corn biodiesel fuel.
C20	20% Corn methyl ester biodiesel +80 Neat diesel.
COME	Canola oil methyl esters.
D	Diesel fuel.
EGR	Exhaust gas recirculation, %.
ICE	Internal combustion engine.
IP	Injection pressure, bar.
m_f	Fuel mass flow rate, kg/s.
NO_X	Nitric oxide, PPM.
RPM	Revolution per minute.
S	Soybean biodiesel fuel.
S20	20% Soybean methyl ester biodiesel +80 Neat diesel.
P_{cyl}	In-cylinder pressure, kPa.
P_{max}	Maximum in cylinder pressure, bar.
T_{exh}	Eexhaust gas temperature, K.
T_{inlet}	Inlet manifold temperature, K.
T_{fuel}	Inlet fuel temperature, K.
T_{wal}	Engine wall temperature, K.
UHC	Unburned hydrocarbon carbon, PPM.
U_R	Uuncertainty in the result “R.
U_{Xi}	Uuncertainty in the variable X_i.
X_i	Variable, i.
T_{inlet}	Inlet manifold temperature, K.
T_{fuel}	Inlet fuel temperature, K.
η_{Bth}	Brake thermal efficiency, %.
η_V	Volumetric Efficiency, %.

INTRODUCTION

Injection pressure (IP) plays an important role in diesel engine performance parameters and emissions. For diesel engine, direct injection fuel system is used to achieve a high degree of atomization in order to enable sufficient evaporation in a very short time and sufficient spray penetration in order to utilize full air charge. The fuel injection system must be able to meter the desired amount of fuel at correct time depending on engine speeds and loads. Reddy et al. [1] studied effects of IP on combustion and emissions for diesel engine using cotton seed oil methyl ester blends with diesel fuel. Authors concluded that as IP increased from 170 to 200 bar, η_{Bth} increased and brake specific fuel consumption (BSFC) reduced. Kumar et al. [2]

studied effect of compression ratio, fuel atomization, IP, fuel quality, combustion rate, A/F ratio, intake temperature and pressure on engine performance parameters. Authors conclude that, air motion in compression ignition engine (CIE) improves fuel atomization, heat release rate and reduces exhaust gas emissions.

Sayin et al. [3] studied effect of fuel atomization and distribution through combustion chamber using a single cylinder diesel engine with canola oil methyl esters (COME) and its blends with diesel fuel. The experimental results showed that fuel exhibit different combustion and performance characteristics for different IP and engine loads. Investigation of injection pressure showed that using COME instead of diesel fuel resulted in earlier injection timing. Maximum P_{cyl}, maximum rate of pressure rise and maximum heat release rate are slightly low for COME and its blend. BSFC for COME are higher than for diesel fuel while $\eta_{Bth,}$ of COME is lower than diesel fuel. Increasing IP gave good results for BSFC and $\eta_{Bth,}$ compared to the original IP.

Kannan and Udayakumar [4] studied effect of IP on performance and emissions from diesel engine. They concluded that good performance and low emissions occurred at IP of 200 bar. Density, viscosity, volatility and molecular structure of biodiesel are higher than neat diesel fuel and have negatively interferes with injection process which leads to poor fuel atomization, incomplete combustion and excessive carbon deposits on fuel nozzles. Nagaraju et al. [5] carried out an experimental study to determine effect of using B20 (20% soybean methyl ester biodiesel and 80% neat diesel fuel) on combustion process, performance and exhaust emissions of diesel engine. Their results indicated that NO_X, CO, UHC and soot for B20 are lower than diesel fuel, while BSFC and T_{exh} are higher with B20 than diesel fuel.

Krahl et al. [6] studied the effect of using biodiesel fuels on gaseous emissions and performance. The results indicated that high BSFC and low brake power (BP) obtained with biodiesel are related to biodiesel low heating value. Jiantong et al. [7] carried out an experimental study on a diesel engine fueled with soybean biodiesel under different engine loads and speeds. The results showed that, BP, BSFC and torque increased with increased biodiesel in the blend. Rosli et al. [8] performed an experimental study to investigate effect of IP from 180 to 220 bar on DI diesel engine performance. According to their results, the best performance is obtained at 220 bar. Purushothaman and Govindan [9] investigated effect of IP on combustion process and exhaust emissions of DI diesel engine fueled with orange skin powder diesel solution. The results indicated that orange skin powder diesel solution gave superior combustion and emissions characteristics as compared to diesel fuel at 235 bar. The aim of the present work is to investigate effect of using soybean and corn biodiesel fuels blends with diesel fuel on engine performance parameters and cylinder pressure.

EXPERIMENTAL SETUP

The present study is conducted on diesel engine at the research lab of Faculty of Engineering, Banha University, Egypt. The experimental setup is shown in Fig. 1. Engine specifications are presented in Table 1a and the test engine operating conditions are presented in Table 1b. Biodiesel fuels are prepared from corn and soybean vegetable oils and properties are determined according to standard ASTM

Table 1a. Technical specifications of the tested diesel engine.

Type	DEUTZ F1L511
Injection	Direct injection
Cooling type	Air cooled
Number of cylinders	1
Number of stroke per cycle	4
Bore, mm	100
Stroke, mm	105
Compression ratio	17:1
Rated brake power, kw	5.775 at 1500 RPM
Advance angle	24^{o} BTDC
Injector pressure, bar	180
Number of nozzle holes	1

Table 1b. Engine operating conditions.

Parameter	Range
Engine speed, rpm	800-1600
Engine Load %	75%
$T_{\textbf{inlet manifold}}$ (K)	298
$T_{\textbf{fuel}}$ (K)	393

and IP methods by Egyptian Petroleum Research Center and the results are given in Table 1c Tests are held on a laboratory test bench which includes an electrical dynamometer coupled to the engine output shaft. It is a DC electric generator (MEZ-BURNO) with maximum electrical power output 10.5 kW. An external excitation of electric circuit is used to generate the generator magnetic field. This circuit consists of an AC autotransformer and a rectifier bridge. The DC generator excitation voltage is controlled and adjusted by the autotransformer. The value of excitation voltage is measured using a digital AC voltammeter (Radio-Shack) of 750 V measurement range and 1volt resolution. The electric power output from the DC electrical generator is consumed in heating water flowing through a water tank.

The present system provides a facility to conduct engine performance tests at different values of engine loads. The loads values are chosen and defined by selecting the generator excitation voltage. Similarly, the engine is said to be working at a certain load ratio when the excitation field voltage applied on the DC generator is adjusted to produce a ratio of engine output power to full load power at the rated engine speed that is equal to the prescribed load ratio. The value of the excitation field voltage corresponding to the prescribed engine load has been maintained constant over the entire engine speed range during a single experiment.

A generator water cooling system has been installed to maintain a constant generator temperature of 298 K during all the experiments. This cooling system has

Table 1c. Physical and chemical properties of diesel, vegetable oils and their biodiesel fuels.

Test Properties	Test Method	Diesel Fuel	Soybean Vegetable Oil	Corn Vegetable Oil	S100 Biodiesel	C100 Biodiesel	S20 Blend	C20 Blend
Chemical formula		$C_{14.09}H_{24.78}$	$C_{56}H_{102}O_6$	$C_{56}H_{103}O_6$	$C_{18.74}H_{34.43}O_2$	$C_{17.89}H_{32.88}O_2$		
Cetane number	ASTM D613	42. 7	38	37.6	51.8	52.5	44.52	44.66
Flash point (℃)	ASTM D93	52	254	277	158.8	165.7	71.6	74.74
Cloud point (℃)	ASTM D2500	-18	-3.9	-1.1	-2	-3	-14.8	-15
Pour point (℃)	ASTM D97	-32	-12.2	-40.0	-6	-5.1	-26.8	-18
Cold filter plugging point (℃)	ASTM D2500	-18	-2	-5	-3.6	-7.5	-5.12	-6.62
Lower heating Value, (MJ/kg)	STM D240	45.9	39.623	35.1	37.75	38.48	44.27	44.42
Density at 40 ℃, (kg/m^3)	TMDA 1298	815	914	915	855	880	823	828
viscosity at 40℃, (mm^2/S)	ASTMD445	3.1	33.1	35.1	4.29	4.5	3.338	3.38
Sulfur content, wt %	ASTMD545	0.22	0.01	0.01	0.0	0.0013	0.001	0.001
Ash content, wt %	ASTMD482-91	0.0055	0.006	0.01	0.006	0.01	0.006	0.01
Carbon residue, wt %	ASTM D4530	0.1780	0.24	0.22	0.244	0.21	0.19	0.18
Distillation Temp., (℃) 90%	STM D86	185 - 345	250 - 445	155 – 365	345	345.8	345	345.2
Carbon content, wt %	ASTM D5291	86.7	78	77.15	77.03	76.71	84.77	84.7
Hydrogen content, (wt %)	ASTM D5291	12.71	11	11.82	11.9	11.52	12.55	12.47
Oxygen content, (wt %)	ASTM D5291	0.0	11	11.02	10.95	10.98	2.19	2.2
Carbon/hydrogen ratio		6.82	6.58	6.52	6.53	6.53	6.67	6.67
Iodine value, g I/100 g	EN 14111	0	120-141	103-128	126	120	25.2	24
Sulfur Content, PPM					2.7	3		

been found essential to avoid the effect of generator internal losses on the accuracy of engine power measurements. The cylinder pressure is measured using piezoelectric pressure transducer model Kistler 6123, 0-200 bar as pressure range with sensitivity of 16.5 pc/bar and accuracy of 1.118 %. The signals from the pressure transducer, optical sensors and thermocouples are digitised and recorded in PC with the help of Lab View software for later analysis using a data acquisition card model CIO-DAS1602/12, 12-bit, 32 channel single-ended 16 differentials. In each test, T_{exh}, T_{wall}, inlet air temperature, differential pressure across orifice plate at inlet air box, engine cylinder pressure and volumetric fuel consumption are measured. For changing fuel type, the engine operates for 30 minutes to ensure that the previous fuel is completed eliminated from fuel system. After that test conditions are adjusted. All the above measured parameters are recorded for each test for 1000000 reading to get the average value for each parameters using Math Lab. Sigma Plot software for plotting the results are used.

Experimental errors analysis

The difference between measured and true value of measured quantity is known as an error. By assigning a value of that error, an uncertainty is defined. The uncertainty in each individual measurement leads to uncertainty in result "R". In general, if the result R is determined by an equation involving "n" independent variables X_i as:

$$R = R(X_1, X_2, ..., X_n)$$

The uncertainty in each independent measurement variable X_i is called U_{X_i} then the uncertainty in R is given by the following equation:-

$$U_R = \sqrt{\left(\frac{\partial R}{\partial X_1}\right)^2 U_{X_1}^2 + \left(\frac{\partial R}{\partial X_2}\right)^2 U_{X_2}^2 \text{..........} + \left(\frac{\partial R}{\partial X_n}\right)^2 U_{X_n}^2} \qquad (1)$$

where U_R is the uncertainty in the result "R", U_{Xi} is the uncertainty in the variable X_i, and the partial derivative $\frac{\partial R}{\partial X_i}$ is a measure of the sensitivity of the result to a single variable X_i.

Equation (1) is the most general form of the uncertainty propagation equation. The measured variables X_i and their uncertainties U_{Xi} are assumed to be independent of one another.

Equation (1) is useful if its transfer to non-dimensional form. Dividing each term by R^2 and multiplying each term on the right-hand side by $(X_i/X_i)^2$, we obtain

$$\frac{U_R}{R} = \sqrt{\left(\frac{X_1}{R}\frac{\partial R}{\partial x_1}\right)^2 \left(\frac{U_{X_1}}{X_1}\right) + \left(\frac{X_2}{R}\frac{\partial R}{\partial x_2}\right)^2 \left(\frac{U_{X_2}}{X_2}\right) \text{..........} + \left(\frac{X_n}{R}\frac{\partial R}{\partial x_n}\right)^2 \left(\frac{U_{X_n}}{X_n}\right)} \qquad (2)$$

In equation (2), U_R/R is the relative uncertainty in the result R and the factors U_{Xi}/X_i are the relative uncertainties of each variable X_i. The factors in parentheses that multiply the relative uncertainties of the variables are called uncertainty magnification factors (UMFs). They indicate the influence of uncertainty in a particular variable on the uncertainty in the result R. Using equation (2) to calculate U_R/R for each measured variable and the results are as follows:-

Item	**T_{exh}**	**T_{wall}**	**m_{air}**	**m_f**	**RPM**	**BP**	**BSFC**	**η_{Bth}**	**η_V**	**P_{cy}**	**$\mu_{Viscosity}$**	**CA deg.**
U_R/R (±%)	2	3	4	3	3	2	2	1	1.5	3	2	3

RESULTS AND DISCUSSION

Fuel Viscosity and Density

Egyptian diesel fuel (No. 2 D) is the base fuel. Corn and soybean biodiesel fuels are prepared from corn and soybean vegetable oils at Egyptian international research center. Fuels properties are recorded in Table 1c. The flash point of biodiesel fuels is higher than diesel fuel indicating low volatile nature for biodiesel fuels. The firing point of biodiesel fuels is very high comparing to diesel fuel indicating that biodiesel fuels are safer in storing than diesel fuel. The distillation temperature range of biodiesel fuels is wider than diesel fuel. The carbon residue of biodiesel fuels is higher than diesel fuel which increases the chance of carbon deposition in the combustion chamber. The high carbon residue for biodiesel fuel is due to difference in chemical composition and molecular structure. Diesel fuel with high percentage of aromatics tends to has high energy content per liter even the aromatics have low heating value per kilogram. Biodiesel high density compensates low energy content on weight basis. This is importance for diesel engines because fuel is metered volumetrically. Aromatics are a class of hydrocarbon compounds that are characterized by stable chemical structure. They are present in diesel fuel in range 25 to 35%. They are considered desirable by diesel engine operator because they provide greater energy per liter. The fuel injection system advances fuel injection timing when fuel flow rate increased. Too high or too low cetane number (CN) causes operation problems. If CN is too high, combustion can occur before mixing fuel and air, resulting in incomplete combustion and smoke. If CN is too low, engine roughness, misfiring, high air temperature, slow engine warm-up and incomplete combustion occur. Most engine manufacturers design to operate with CN in range of 40–50.

Viscosity is one of the most important properties of biodiesel fuel. Viscosity increases with increased chain length (number of carbon atoms) and degree of saturation. Double bond configuration influences viscosity whereas double bond position affects viscosity less Purushothaman and Govindan [9]. High viscosity of biodiesel decreases fuel leakage in a plunger pair and in changes the parameters of the fuel supply process: quantity fuel injection, IP, injection timing, real injection angle influence harmful emissions of exhaust gas. High viscosity effects fuel atomization and forming carbon deposits. Viscosity influences engine starting, fuel spray quality, droplet size, fuel penetration and combustion quality. The fuel with low viscosity provides fine spray, low mass and speed. This leads to insufficient penetration and formation of black smoke specific to combustion in absence of oxygen. A high viscous biodiesel leads to formation of big droplets, which will penetrate to the wall opposite to the injector. The cylinder surface is being cold, it will interrupt combustion and blue smoke will form. Also, high viscosity leads to increase cylinder wall deposits and increases fuel pumping energy, as well as increases wear of the pump and the injector elements due to high mechanical effort. Viscosity and density for different fuels versus temperature are shown in Fig. 2.

Viscosities of diesel and biodiesel fuels decrease with increased temperature. By increasing fuel temperature, the inter-molecular attraction between different layers of the fuel decreases and consequently viscosity decreases, Purushothaman and Govindan [9]. Fuel viscosity increases with increased of biodiesel percentage, therefore corn oil and soybean oil are transesterified to biodiesel to decrease fuel viscosity. Viscosity and density of diesel fuel are lesser than soybean and corn biodiesel fuels respectively. The difference between viscosity of biodiesel and diesel fuels are maximum at low temperature and minimum at high temperature. Viscosities of corn and soybean biodiesel fuels are less than viscosities of their vegetable oils due to glycerin separation. The maximum difference between viscosities of C20, S20 and D100 are obtained at 40°C. In order to bring physical properties of C20 and S20 biodiesels close to diesel fuel at (30°C), biodiesels need to be heated to 60-80 °C. For temperature range below 60 °C, it is necessary to keep biodiesel percentages as low as possible.

Fuel density is major parameter that affects atomization and combustion processes. Where fuel system of diesel engine (pump and injectors) meters fuel by volume so, modification of fuel density affects mass of fuel injected into engine cylinder and energy content of the fuel dose altering the fuel/air ratio and engine power. Fuel density decreases with increased temperature. For different temperatures, the decrease in density is observed with increased diesel fuel percentage. The density of C20 and S20 biodiesels blends are closed to diesel fuel. Fuel density and viscosity decrease with increased temperature and affect fuel spray, emissions and combustion characteristics in engine cylinder. Fuel density decreases linearly with increased fuel temperature while viscosity decreases exponentially. Biodiesel fuel is used as alternative fuel for diesel engines due to properties of biodiesel fuel are close to diesel fuel.

Mass of Fuel Injected and Air/Fuel Ratio for Different Operating Conditions

Figures 3a, 3b and 3c show mass of fuel injected per cycle versus engine speeds for different fuels with different engine loads and IP. Mass of fuel injected for C20 and S20 blends have similar trends as diesel fuel. For all tested fuels, mass of fuel increases with increased engine speeds, loads and IP. Engine speed and load are affected mass of fuel injected more than fuel type and IP. Mass of fuel injected for C20 and S20 are higher than neat diesel fuel for different engine loads and speeds. This is due to equivalent heat content must be injected into engine cylinder per cycle for different fuels. The mass of C20 is higher than S20 and diesel fuels due to C20 have the lowest heating value. For the same heat release, mass of fuel injected per cycle for C20 and S20 blends are higher than neat diesel fuel due to low heating value. For the same engine speed, mass of fuel injected for C20 and S20 are higher than neat diesel due to high viscosity which reduces normal injection pump leakage to make a significant change in the volume discharged per stroke. Plunger begins to vaporize the residual fuel in pump cylinder near end of the pumping stroke. An amount of C20 and S20 evaporates on pump cylinder surface which increases volumetric efficiency of fuel pump and quantity of fuel injected. The amount of C20 and S20 evaporate on pump cylinder surface is related to high distillation temperature of C20 and S20. Mass of fuel injected for C20 is higher than S20 and neat diesel fuels due to: (1) High viscosity, density and IP; (2) Minimum fuel leakage from pump plunger; (3) Advance injection timing and long duration of injection. Mass of fuel injected is arrangement in descending order as C20, S20 and neat diesel fuel respectively according to their viscosity and density.

A/F ratio affects combustion process through effecting on flame velocity, heat release rate, maximum flame temperature and completeness of combustion. For diesel engine, at a given speed and load constant air supply enters engine cylinder. Therefore diesel engine is termed as constant air supply engine and consequently A/F ratio changes based on mass of fuel injected per cycle. A/F ratio decreases with increased engine speed load and IP due to increase mass of fuel injected per cycle. For diesel engine A/F ratio at low and middle engine loads is higher than at full load due to decrease mass of fuel injected. Also, A/F ratio at low and middle engine speeds is higher than at high engine speeds. For all tested fuels A/F ratio decreases as IP increases due to increase of pressure difference across fuel nozzle orifice which increases mass of fuel injected. For the same engine speed and load, C20 and S20 have A/F ratio lower than diesel fuel due to high mass of fuel injected. A/F ratio is arranged in descending order as diesel, S20 and C20 respectively.

Engine Performance Parameters

Engine performance parameters versus engine speeds for different fuels and loads are shown in Fig. 4. For all tested fuels, BP increases with increased engine speeds and loads due to increase mass of fuel burning. For engine load of 83 %, BP for S20 is higher than that for diesel fuel and C20 respectively. This is due to improve atomization process for S20 than diesel fuel with high IP of 200 bar (the normal IP of engine is 180 bar). On the other hand viscosity, density and heating value of S20 are lower than that for C20. For engine load of 50 %, BP for C20 and S20 are lower than diesel fuel due to high viscosity and poor atomization and inadequate burning rate due to low heating value. S20 and C20 have heating value lower than neat diesel fuel, so without any change in the fuel system (i.e. for the same volume of fuel injected) S20 and C20 give BP lower than diesel fuel. BP for S20 and C20 are very close especially at the middle speeds and loads. For engine load of 67 % all fuels have nearly the same BP except at low engine speeds diesel fuel has BP higher than S20 and C20 respectively. The difference in BP between different fuels increase with increased engine speeds and loads due to increase mass of fuel burning. The power losses due to using S20 and C20 partially recovered by advanced injection timing. This is due to S20 and C20 have CN lower than diesel fuel.

Brake specific fuel consumption (BSFC) for all fuels decreases with increased engine speeds and loads due to rate of increasing BP is higher than rate of increasing mass of fuel burning. For high engine speeds and load of 83 % BSFC for S20 is lower than diesel fuel and C20 respectively due to S20 has high BP. Also, at high engine speeds the turbulence intensity increases which improves combustion quality and decreases mass of fuel unburned. But at low engine speeds and load of 83 %, BSFC for S20 is higher than C20 and diesel fuels respectively due to the highest mass of fuel injected. For low engine load of 50 %, BSFC for C20 is higher than for neat diesel and S20 respectively. This is due to combined effects of high viscosity, density and low heating value of C20 which leads to the largest fuel consumption in order to release the same energy as that for diesel fuel. Also, C20 has BP lower than neat diesel and S20 fuels and higher mass of fuel injected than S20 and neat diesel fuels respectively. This is consistent with the fact that BSFC increases with decreased gross heating value to supply the same BP (fuel has lower heating value consumed at higher rate). So, an increase in BSFC is observed for S20 and C20 due to high viscosity/density and low heating value as compared to diesel fuel. Hence BSFC curve for C20 lay above curves for neat diesel and S20 respectively. C20 fuel has BSFC higher than S20 due to low heating value, high viscosity and density of C20 compared to S20. For low engine speeds and load of 67 %, BSFC for C20 is higher than neat diesel and S20 respectively while at high engine speeds and load of 67 % all fuels have nearly the same BSFC. Biodiesel trends follow neat diesel fuel where BSFC reduces with increased load and the values tend to converge at approximately similar values at full load.

Brake thermal efficiency (η_B) increases with increased engine speeds and loads due to rate of increasing BP is higher than rate of increasing mass of fuel burning and

A/F ratio goes to stoichiometric condition which increases heat release rate. For high engine speeds and different engine loads η_B for S20 is higher than neat diesel and C20 fuels respectively due to improve combustion quality for biodiesel than neat diesel fuel. Also, 200 bar as IP has more affected for improving atomization process with biodiesel than neat diesel. For low engine speeds and engine loads of 83 %, and 67 % S20 has η_B higher than neat diesel and C20 respectively. S20 gives BP and η_B higher than C20 due to (1) High heating value, (2) Low viscosity which affects atomization process and combustion quality, and (3) Low heat losses in exhaust gases. η_B for neat diesel, S20 and C20 are arrangement inversely according to their viscosity, density and oxygen content in molecules but arrangement in descending order according to their heating value. High viscosity decreases combustion quality due to increase fuel mean droplet diameter leading to poor atomization. On other hand oxygen content in S20 and C20 molecules improves combustion quality and decreases heat of combustion. So, the drop in η_B with C20 fuel prove that poor combustion of biodiesel fuel is due to high viscosity and poor volatility which overcoming excess oxygen content in the biodiesel molecule. The difference in η_B between S20 and C20 at low engine speeds is lower than at high engine speeds due to increase turbulence intensity and mass of fuel burning. η_B increases with increased engine speed due to increase BP. η_B increases with increased BP and the peak value of η_B is closed to that at full load. Improve of η_B is more significant at full loads than at part loads. At high engine BP, the combustion chamber temperature is relatively high and this assists vaporization of fuel and improves $\eta_{B,}$ Siva et al. [10]. η_B increases with increased engine load, especially above 50 % of engine load the effect is quite dramatic. This effect is related to lean condition of premixed flame at part load (slow flame propagation).

Volumetric efficiency (η_V) for S20 and C20 is higher than neat diesel fuel due to high latent heat of vaporization resulting in cooling air/fuel mixture compared to neat diesel fuel. S20 has the highest η_V for the three tested fuels. Although the mean temperature of the heat transfer surface increases, the coefficient of residual gas slightly increases which reduces the coefficient of admission (volumetric efficiency). η_V is inversely proportional to engine speed and drops exponentially with engine speed. η_V decreases with increased engine speed due to increase mass of air entering engine cylinder with decreased suction pressure. But the rate of increasing air mass flow rate is lower than the rate of increasing engine speed, so, η_V decreases with increased engine speed. Further increase in engine speed does not increase air flow rate significantly so η_V decreases sharply. The sharp decrease happens due to high speed is accompanied by heating of charge in the inlet manifold and high friction flow losses which increases as the square of engine speed. At high engine speeds and loads, engine parts have high temperature which decreases air density and η_V. η_V for diesel fuel is higher than biodiesel fuel due to increase air flow rate entering to engine cylinder. Also, T_{exh} for biodiesel fuels are higher than diesel fuel. This means that biodiesel fuel has volume and pressure of residual gas higher than diesel fuel which decreases mass of fresh air entering to engine cylinder. Finally engine performance parameters for S20 and C20 are in good conditions than that for neat diesel fuel at high engine speeds, loads and IP.

Exhaust and Wall Temperatures

Exhaust gas temperatures (T_{exh}) for all tested fuels are shown in Fig. 5. For all tested fuels T_{exh} increases with increased engine speed and load due to increase rate of heat release. T_{exh} for C20 and S20 is slightly lower than that for diesel fuel with similar trends. Reduction of T_{exh} for C20 and S20 can be attributed to low combustion temperature leading to low exhaust temperature. In addition heating value of diesel fuel is higher than for C20 and S20, therefore high heat is release rate is generated in combustion chamber leading to high temperature. As engine load increases T_{exh} increases. Increasing engine load is a direct effect on increasing mass of fuel injected so, more heat generates during combustion and this is consistent with Sharanappa et al. [11]. In addition at high engine speeds, combustion is completed in the exhaust system leads to increase T_{exh}. Fuel of high heating value exerts high energy during combustion process which increases T_{exh}.

Wall temperature (T_{wall}) for S20 and C20 are higher than diesel fuel, this is attributed to high BSFC as a result for increasing heat lost to the cylinder wall. The lack of complete combustion due to high viscosity increases T_{exh} contributing to increase heat loss to cylinder wall and consequently increases T_{wall} for S20 and C20 than diesel fuel. Also, variation of T_{wall} for C20 is high than S20 due to high viscosity. T_{Wall} for diesel fuel is lower than for C20 and S20 fuels due to lower amount of fuel burning where the mass of fuel burned per unit power (BSFC) for C20 and S20 fuels is higher than for diesel fuel. From energy balance, if the exhaust losses and BP for diesel fuel are higher than C20 and S20, consequently heat losses to engine cylinder wall for C20 and S20 must be higher than for diesel fuel.

Engine Cylinder Pressure Analysis

Cylinder pressure (P_{cyl}) versus engine crank angles for different fuels, loads and IP are shown in Fig. 6a. High viscosity, poor atomization and low heating values for C20 and S20 give P_{cyl} lower than diesel fuel. For all tested fuels, P_{cyl} increases with increased engine load and IP due to increase heat release rate, mass of fuel burning and A/F ratio goes to stoichiometric condition. P_{cyl} is mainly depended on mass of fuel burning during premixing phase and ability of fuel to mix well with air. Premixing phase is generated by ignition delay period and by mixture preparation during the delay period. Also, P_{cyl} depends on rate of heat release in initial stages of combustion which influence by CN and mass of fuel burning in premixing phase. CN for diesel fuel is lower than for C20 and S20 fuels, so ignition delay for C20 and S20 is shorter than diesel fuel. Therefore, start of combustion for S20 and C20 is earlier than neat diesel fuel. Consequently rate of pressure rise for S20 and C20 is started earlier than neat diesel fuel. So, P_{cyl} for S20 and C20 for initial and premixing phases of combustion are higher than neat diesel fuel while P_{cyl} for neat diesel fuel is the highest at the end phase of combustion. The effect of engine load on maximum cylinder pressure (P_{max}) at 1200 rpm for different fuels and IP is shown in Fig. 6b. For different fuels, P_{max} increases with increased engine load and IP due to increase mass of fuel burned and heat release rate. For CIE, P_{max} depends on rate of fuel burning in the initial stages which influences by amount of fuel burning taking part from uncontrolled combustion phase, which governs by delay period, Heywood [12]. For same engine load and 190 bar as IP, P_{max} for C20 is higher than for neat diesel and S20 fuels respectively due to high CN and short delay period. On the other hand for 190 bar as IP, C20 and S20 have a high viscosity, density, flash point and a low volatility result in inferior atomization and vaporization. These parameters lead to reduce air/fuel mixing rate while increased mass of fuel burning rate in the diffusion phase. Also in the range of 0-50 % loads, with IP of 200 bar, C20 and S20 have P_{max} lower than neat diesel fuel due to low cylinder gas temperature and high viscosity of biodiesel compared to diesel fuel, which affecting fuel atomization and combustion processes. In range of 50-100 % loads, P_{max} for neat diesel fuel becomes close to C20 and still higher than S20. .For IP of 200 bar neat diesel fuel exhibits P_{max} higher than C20 and S20 due to low viscosity, good mixing, high heating value and heat release rate. P_{max} has the arrangement in descending order as C20, diesel and S20 respectively.

Positions of P_{max} versus engine loads for all fuels with different IP are shown in Fig. 6c. Position of P_{max} for C20 for different engine loads are more delayed ATDC than for neat diesel and S20 fuels due to the highest viscosity, density and mass of fuel injected. This reaffirms slow burning rate of C20 compared to diesel fuel and S20 blends. For C20, short ignition delay tends to advance position of P_{max} but high viscosity tends to retard injection timing ATDC. For neat diesel, long ignition delay tends to retard position of P_{max} but low viscosity tends to advance injection timing ATDC. So, for all tested fuel effect of viscosity on combustion characteristics is higher more than effect of CN. The position of P_{max} ATDC is arrangement in descending order as S20, neat diesel and C20 respectively. On contrast self-ignition temperature for diesel fuel is lesser than C20 which increases rate of pressure rise and complete combustion early. For three fuels, position of P_{max} as CA deg. ATDC decreases with increased engine load up to 50 % after that the trend is reversed. Position of P_{max} is attained within 14-18° ATDC for all fuels with different IP and loads. Start of combustion for all fuels close to each other with increased load. The differences in position of P_{max} ATDC between the different fuels are in ringed of 1-2 CA deg. Furthermore as IP increases from 190 to 200 bar position of P_{max} as CA deg. ATDC for different fuels decreases in case of 200 bar more than for 190 bar, especially at a high loads. This is postulated to improve atomization and air/fuel mixing. For 200 bar as IP; position of P_{max} CA deg for different fuels at high load decreases than at low load. This attribute to decrease ignition delay as engine load increases due to high gas temperature inside engine cylinder which reduces the physical ignition delay, early combustion and high rate of pressure rise. Position of P_{max} as CA deg. ATDC has the arrangement in descending order as C20, neat diesel and S20 respectively.

CONCLUSIONS

1. A successful operation of diesel engine fuelled by C20 and S20 biodiesel blends with diesel fuel over a wide range of engine speeds, loads and IP without any hardware modification.
2. For high engine speeds, loads and IP mass of fuel injected, BP, η_{Bth}, η_V, T_{Wall}, and P_{cyl} for S20 are higher than for neat diesel fuel while A/F ratio, BSCF and T_{exh} for S20 are lower than for neat diesel fuel.
3. For all fuels effect of viscosity on combustion characteristics is more than effect of CN.
4. For S20 and C20 optimum IP is 200 bar where the highest BP and η_{Bth} and the lowest BSFC are obtained. Increasing IP by 15 % (from 180 to 210 bar) for S20 and C20 improves performance parameters than neat diesel fuel. This is due to

S20 and C20 have viscosity and density higher than neat diesel fuel and the improvement in atomization process is better than that for neat diesel fuel.
5. For 190 bar as IP, P_{max} with C20 is higher than for neat diesel and S20 respectively. For 200 bar as IP, P_{max} for neat diesel fuel is higher than for C20 and S20 due to good mixing, high heat release rate.
6. Position of $P_{max.}$ is attained within 14-18° CA deg. ATDC for all fuels with different IP, speeds and loads. The difference in position of $P_{max.}$ ATDC for all fuels are in rang of 1-2 CA deg. with different engine speeds, IP and loads.

REFERENCES

[1] Subba Reddy V. C., Eswara Reddy C. and Hemachandra Reddy K., Effect of fuel injection pressures on the performance and emission characteristics of DI diesel engine with biodiesel blends cotton seed oil methyl ester, IJRRAS 2012; Vol. 13: pp. 139-140. Issue (1).
[2] Deva Kumar S. L. M., Drakshayani S., Vijaya Kumar Reddy Kumar Vijaya K., Effect of fuel injection pressure on performance of single cylinder diesel engine at different intake manifold inclinations, Certified International Journal of Engineering and Innovative Technology (IJEIT) October 2012; Vol. 2: Issue 4.
[3] Sayin Cenk, Gumus Metin, Mustafa Canakci Mustafa, Effect of fuel injection pressure on the injection, combustion and performance characteristics of a DI diesel engine fueled with canola oil methyl esters-diesel fuel blends, Biomass and Bioenergy 2012; Vol. 46: pp. 435-446.
[4] Kannan K. and Udayakumar M., Experimental study of the effect of fuel injection pressure on diesel engine performance and emission, Journal of Engineering and Applied Sciences 2010: Vol.: 5, pp. 42-45.
[5] Nagaraju, V., Henein, N., Quader, A., Wu, M., Bryzik, W., Effect of biodiesel (B-20) on performance and emissions in a single cylinder HSDI diesel engine, SAE Technical Paper Series 2008-01-1401.
[6] Jurgen Krahl, Gerhand Knothe, Axel Munack, Yvonne Ruschel, Olaf Schroder, Emst Hallier, Gotz Westphal, Jurgen Bunger, Comparison of exhaust emissions and their mutagenicity from the combustion of biodiesel, vegetable oil, gas-to-liquid and petrodiesel fuels, Fuel 2009; Vol. 88: pp. 1064-1069.
[7] Song Jiantong, Yao Jvbiao, Lv Jiangyi and Zhu Chunhong, Experimental study on a diesel engine fueled with soybean biodiesel, Research Journal of Applied Sciences, Engineering and Technology 2013; Vol. 6(16): pp. 3060-3064.
[8] Rosli Abu Bakar, Semin and Abdul Rahim Ismail, Fuel injection pressure effect on performance of direct injection diesel engines based on experiment, American Journal of Applied Sciences 2008; Vol. 5(3): pp. 197-202, ISSN 1546-9239.
[9] Purushothaman, K., Govindan, N., Studies on a CI engine using orange skin powder diesel solution with different fuel nozzle opening pressure, Thermal Science 2009; Vol. (13) 3: pp. 103-112.
[10] Siva, A. K., Maheswar, D. K., Vijaya, K. R., Comparison of diesel engine performance and emissions from neat and transesterification cotton seed oil. JJMIE 2009; Vol. 3: pp. 190-197, ISSN 1995-6665.
[11] Sharanappa, G., Suryanarayana, M., Rana, P. R., Performance and emission characteristics of kirloskar HA394 diesel engine operated on mahua oil methylester. Thammasat Int. J. Sc. Tech. 2010; Vol. 15: No. 3.

[12] Heywood, J. B. 1998, Internal combustion engines fundamentals, Mc Graw Hill International Edition, Singapore.

Figures:

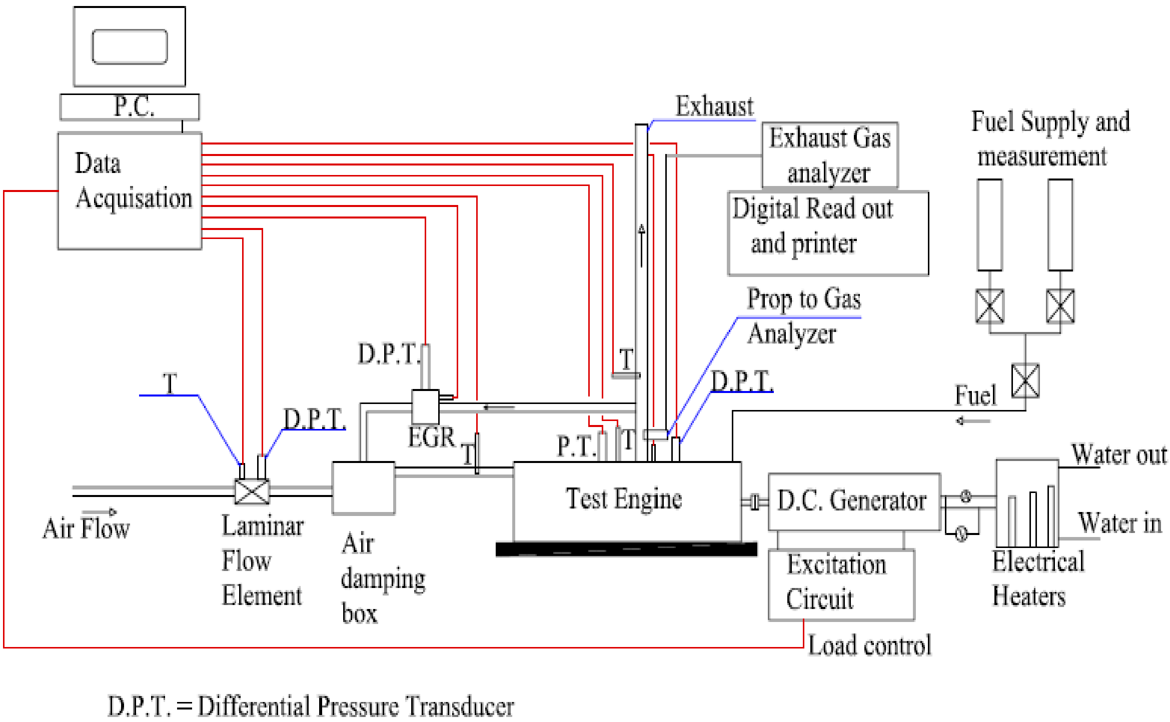

Fig.1. Experimental setup.

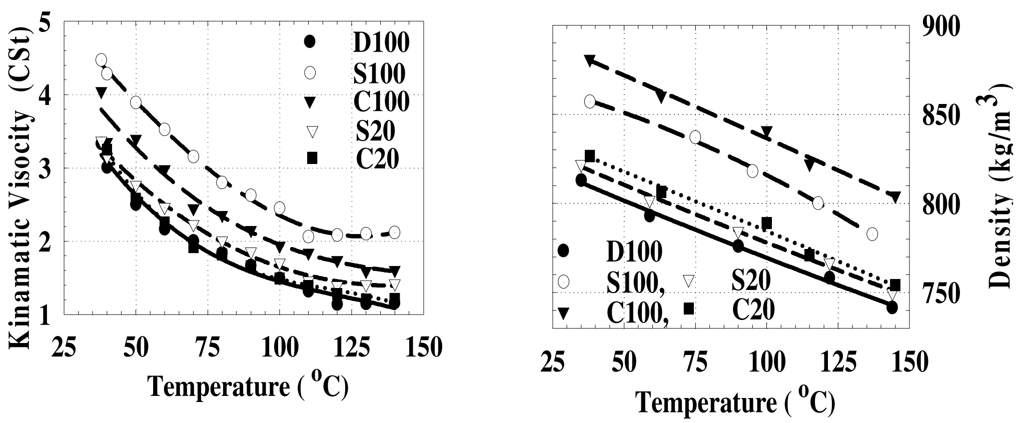

Fig. 2. Viscosity and density of different fuels versus temperature.

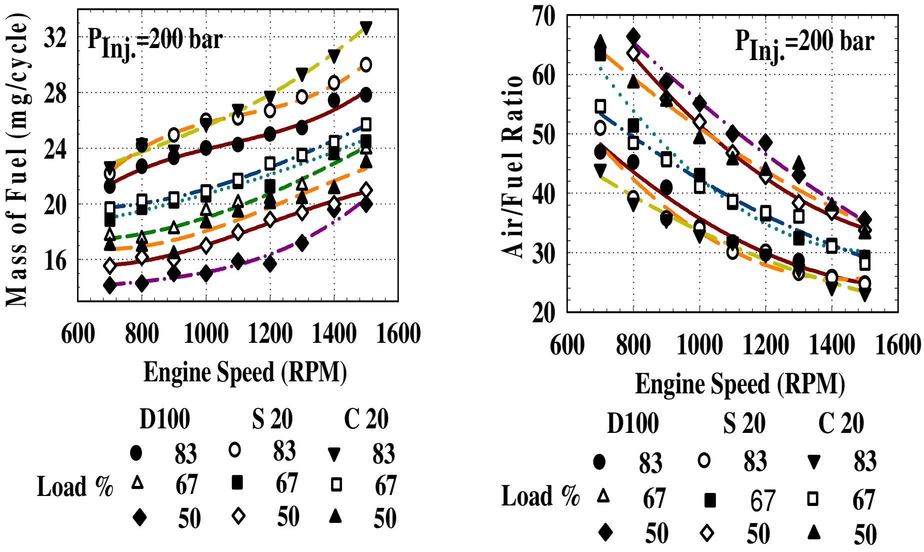

Fig. 3a. Mass of fuel injected and Air/Fuel ratio for different fuels and loads with injection pressure of 120 bar.

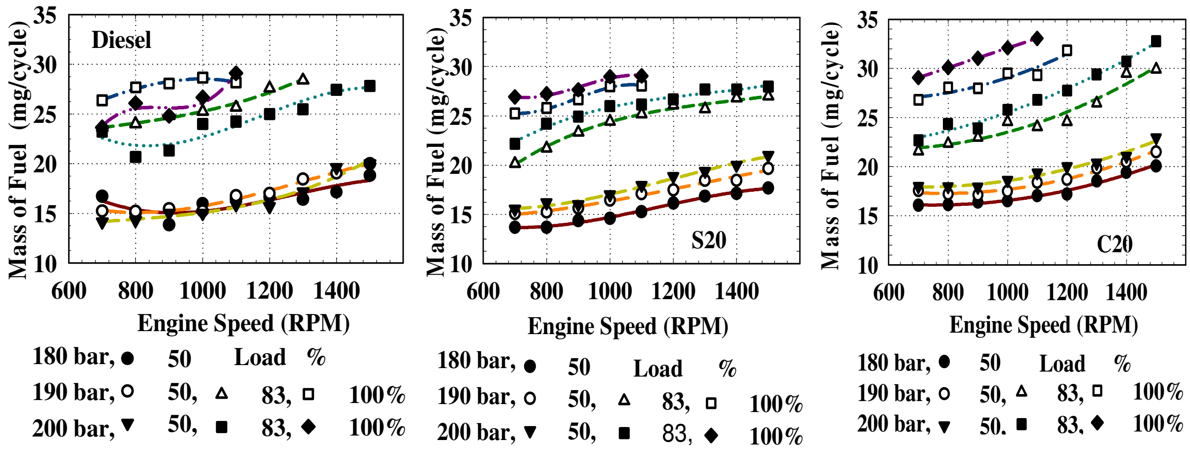

Fig. 3b. Mass of fuel injected with different fuels, loads and injection pressures.

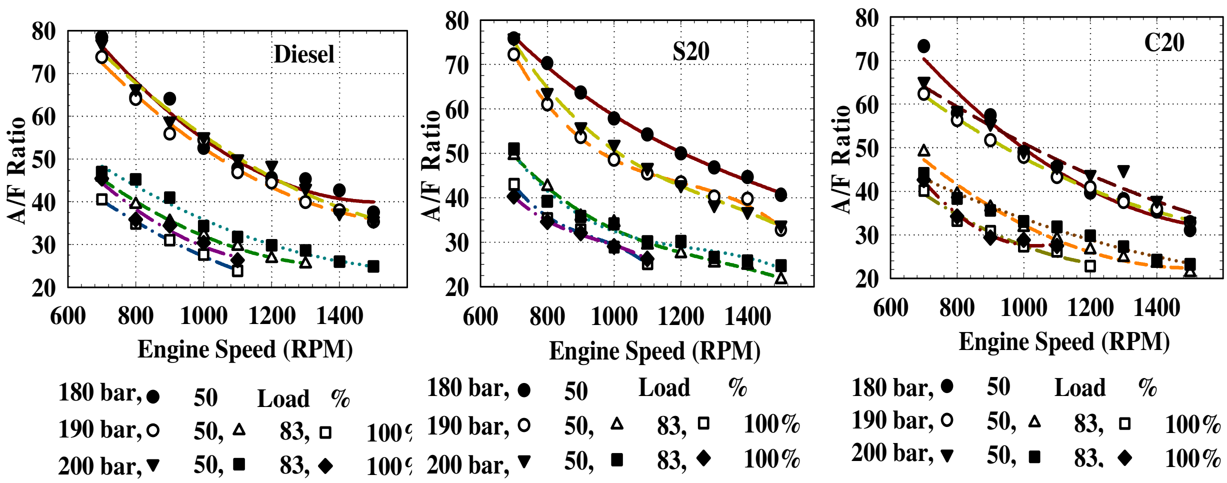

Fig. 3c. Air/Fuel ratio with different fuels, loads and injection pressures.

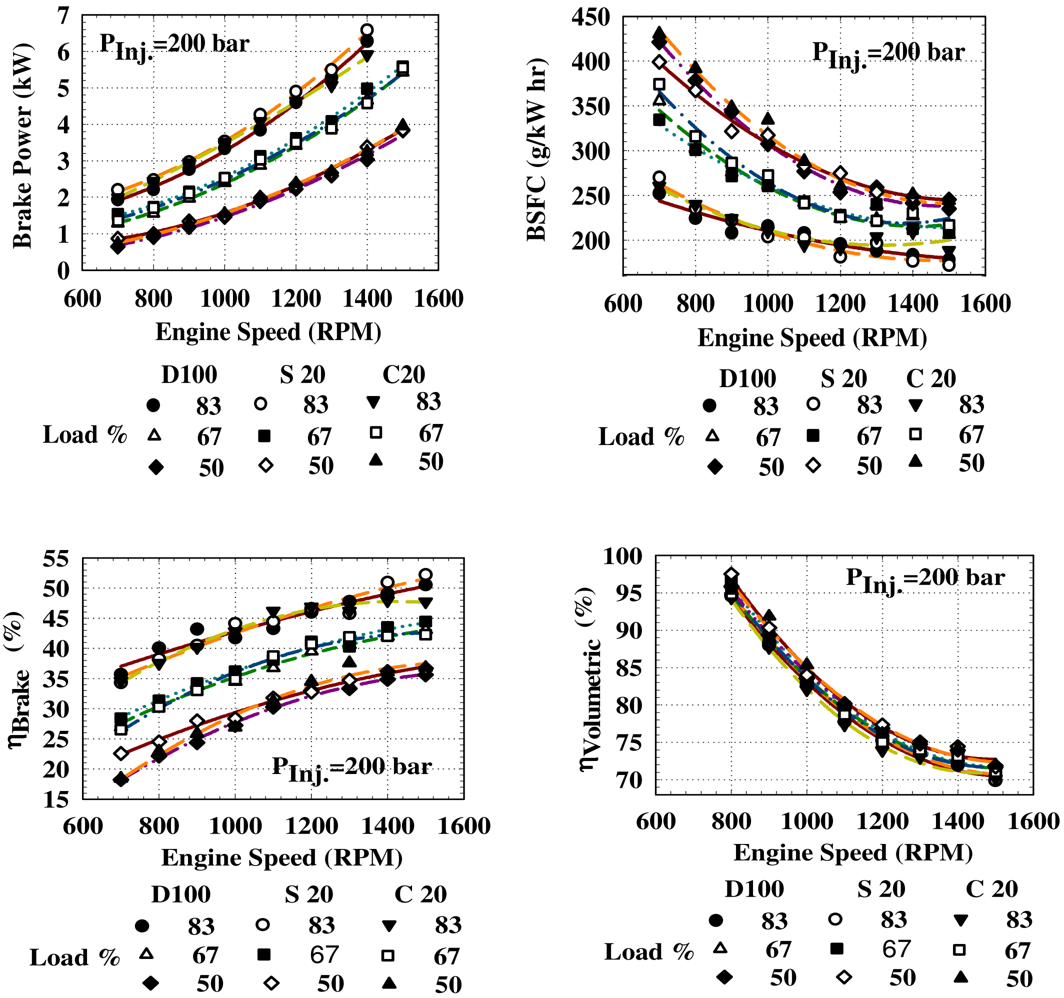

Fig. 4. Engine performance parameters versus engine speeds for different fuels and loads with injection pressure of 200 bar.

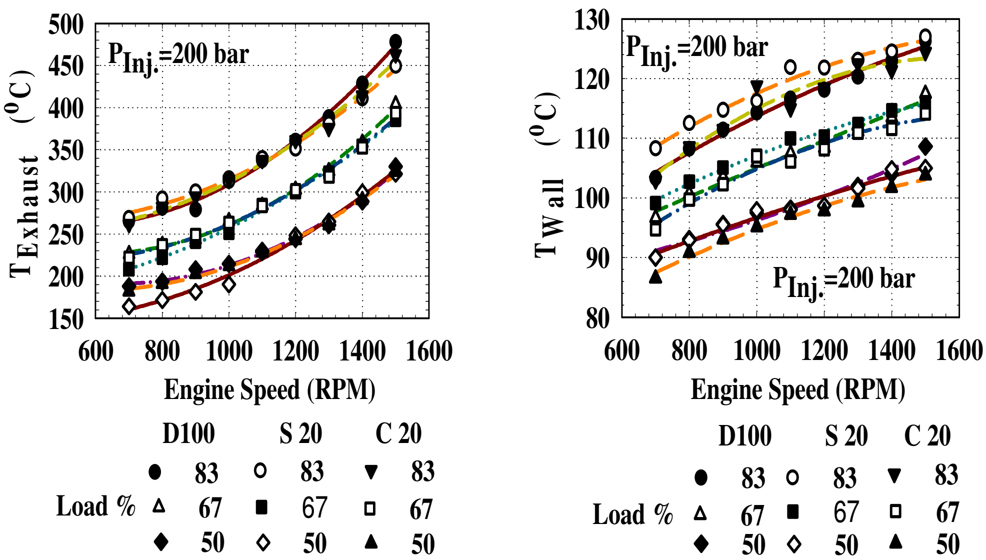

Fig. 5. Exhaust gas temperature and wall temperature versus engine speed for different load and fuels at injection pressure of 200 bar.

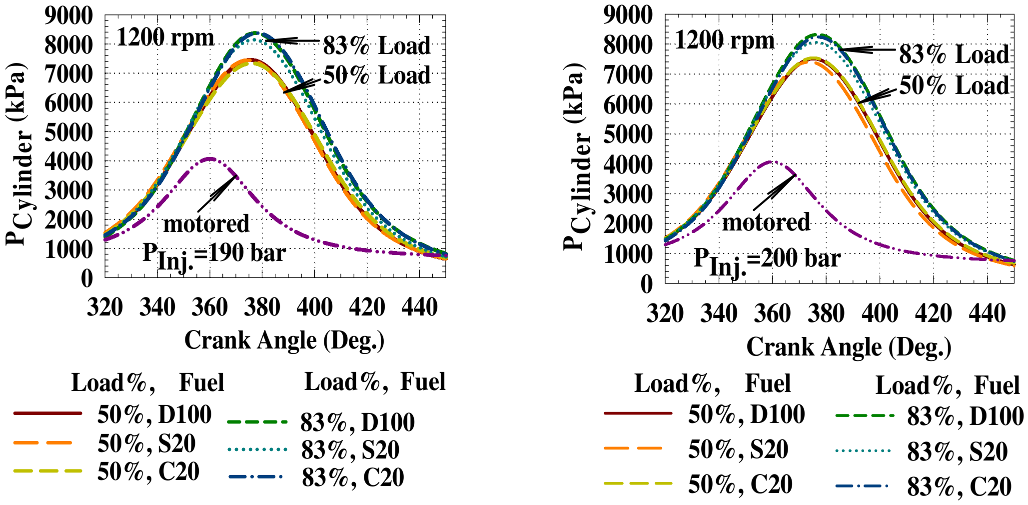

Fig. 6a. Cylinder pressure at 1200 RPM for different fuels, injection pressures and loads.

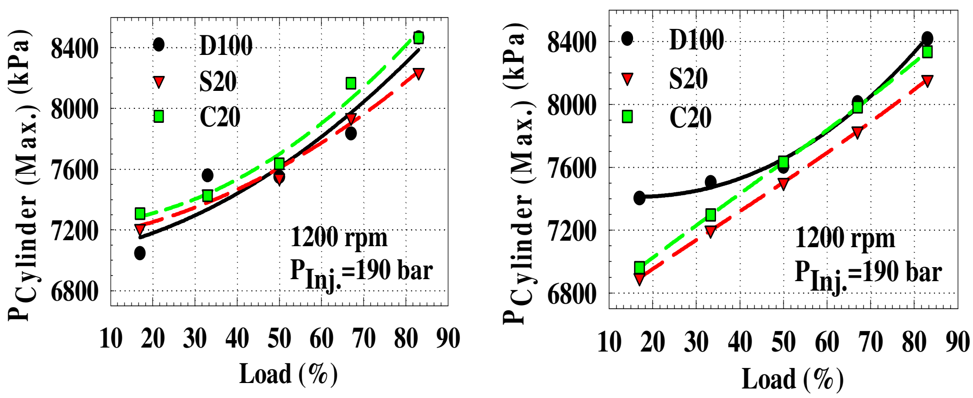

Fig. 6b. Maximum cylinder pressure at 1200 RPM for different fuels, injection pressures and loads

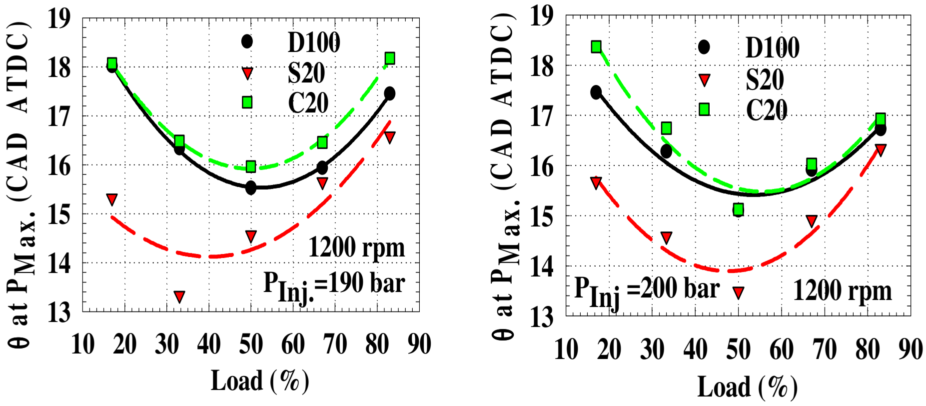

Fig. 6c. Position of maximum cylinder pressure at 1200 RPM for different fuels, injection pressures and loads