An Experimental Assessment on the Influence of High Fuel Injection Pressure with Ternary Fuel (Diesel-Mahua methyl ester-Pentanol) on Performance, Combustion and Emission Characteristics of Common Rail Direct Injection Diesel Engine

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Abstract

This paper deals with analysis of the influence of fuel injection pressure with ternary fuel (diesel + Mahua methyl ester + Pentanol) on the emission, combustion and performance characteristics of a four stroke, single cylinder, common rail direct injection diesel engine working at a constant speed and varying operating scenarios. The usage of ternary fuel raised the NO_x emission (12.46%) value and specific fuel consumption (SFC) with a decrease in the BTE (brake thermal efficiency) which attributes to its properties and combustion characteristics. The combustion process was affected by the physical properties of the blended fuel such as volatility and viscosity and this eventually affected the performance of the engine. The fuel injection pressure is varied from 20 MPa to 50 MPa so that ternary fuel can be properly utilized. The high injection pressure of 50 MPa has better combustion characteristics and higher brake thermal efficiency (4.39%) value than other injection pressure values. A better mixture is formed due to well atomized spray and as a result, the levels of CO (22.24%), HC (9.49%) and smoke (7.5%) falls with the increase in injection pressure.

Introduction

Due to the heavy usage of fuels around the world, fuel energy demand is increasing at a speedy rate. Also, fossil fuel resources are depleting and due to increased environmental concern, the development of alternate energy sources like biodiesel are emphasized more than anticipated. The biodiesel's history is as old as the history of normal engine and moreover, the use of SVO was also thoroughly studied at the time when the diesel engine was invented. (Rakopous et al. 2008) investigated the influence of alcohol with different concentrations (10% and 5%) along with diesel fuel. There was a significant improvement in the performance of the engine and the emission characteristics while using 10% ethanol-diesel blend when compared with the 5% blend of same. Selvan et al. (2009) studied about the effect of CO (cerium oxide) nano additive concentration in ethanol- biodiesel-diesel blends and results revealed that there was an increase in fuel consumption whereas brake thermal efficiency reduced when compared to conventional diesel fuel. (Barabas et al. 2010) investigated on multi cylinder CI with bio-ethanol/biodiesel/diesel and studied about the emissions and performance characteristics and reported that at part loads, the reduction in performance because of less heating value. Carbon monoxide and hydrocarbons emissions were reduced while using biodiesel-diesel-ethanol blend. Fang et al (2013) and Qi et al (2011) also submitted alike reports regarding the usage of biodiesel- ethanol- pure diesel blend in diesel engines. Nitrogen oxide emissions were considerably decreased when the ternary blend was used in comparison with pure diesel for entire load conditions. Hulwan et al. (2011) studied about the practicality of ethanol in high concentrations in the diesel-ethanol blends and reported that the nitrogen oxide emissions were increased considerably. However, carbon monoxide emissions increased at smaller loads and smoke opacity reduced for higher loads. (Fang et al. 2013) investigated the characteristics of biodiesel blends which are found to be hygroscopic nature resulting in in stratification and eventually affects the fuel injector as time passes. The occurrence of stratification will be nullified when biodiesel was used with ethanol - diesel blend. So instead of this bi-fuel mixture, a mixture of 3 fuels i.e., alcohol-diesel- biodiesel blend was introduced. Various experimental studies in a diesel engine with ethanol- biodiesel- pure diesel blend as fuel were carried out. An improved model of ethanol- biodiesel- diesel fuel blend was formulated by Lin et al. (2013). They conducted experiments with different fuel blends which can improve the entire profitability of the system, with given the cost of production, prices of fuels etc. Datta and Mandal (2014) studied about the suitability and ANPs at varying concentrations of 100,75,50,25 mg/l with DBF (diestrol blended fuel)- 70% diesel + 20% ethanol + 10% jojoba biodiesel on the utilization of engine characteristics and reported that at a dosage of 25 mg/ l the hydrocarbons and nitrogen oxide emission decreased in comparison with other nanoparticles additives. Sandalc et al. (2014) examined the impact of ethanol on diesel engine under two operating conditions i.e., 30% and 15% diesel fuel levels (on the basis of volume). No separation of phase was observed and the blend of ethanol and diesel was very stable throughout the operation. They also witnessed a considerable decrease in smoke and nitrogen oxide emissions in comparison with diesel fuel. Yilmaz et al. (2014) analyzed the impact of ternary blend and reported that changing ethanol concentrations resulted in varying emission characteristics due to varying oxygen content and cooling effect of ethanol. They concluded that the ethanol concentration in the blend decreased the carbon monoxide and hydrocarbon emissions and increased the nitrogen oxide emissions. Li et al. (2014) investigated the influence of ternary blend in a diesel engine of 1600 rpm speed (constant) and reported that the addition of pentanol resulting in the betterment of air- fuel mixing rate, greater thermal efficiency and lesser emissions. (Shaafi et al. 2015) investigated about the impact of ANP at dosage of 100 mg/l in both ternary blend of 1% surfactant + 4% ethanol + 15% soybean diesel + 80% diesel and binary blends - B2 and reported that the heat release rate and cylinder pressure of ternary blend displayed higher value, due to high value of the surface area to volume ratio of alumina. Venu et al. (2016) studied about the impact of ANP in ethanol - biodiesel-diesel ternary blend at different injection timings and found that the combustion of nanoparticles was effectual in delayed injection timing and decreasing the hazardous tailpipe emissions like nitrogen oxide, carbon monoxide, smoke and hydrocarbons. (Prabu et al. 2016) investigated the influence of nano additives blended with jatropha in a diesel engine and reported that the high brake thermal efficiency of 31% and a decreased value of brake specific fuel consumption of 0.293 kg/kWh.

(Venu et al. 2017) through his studies found that addition of nanoparticles into ternary fuel blend is much better than the addition of oxygenated additives. Hosseini et al. (2017) studied about the impact of ANPs as catalysts in blends of 95% diesel & 5% WCO biodiesel (B5 Blend) and 90% diesel + 10% WCO biodiesel blend (B10 blend) in a diesel engine and reported that B10AL90(90 ppm ANP in B10 blend) shows higher brake thermal efficiency, power, EGT and torque of values of 10.63%, 5.36%, 5.8% and 5.36% respectively when compared to conventional diesel fuel, while brake specific fuel consumption decreased to 14.66%. Venu and Madhavan (2017) investigated the influence of biodiesel blends on CI engine characteristics which uses the blend of diesel-ethanol-biodiesel as ternary fuel. From their study, it was clear that the addition of nano additives resulted in the betterment of engine performance in terms of various parameters. Chokalingam et al (2017) investigated on diesel engine by adding 10% ethanol to diesel and it was observed that the performance was similar to that of diesel fuel. (Nour et al.2018) studied about the ANP (Alumina nanoparticles) at different concentrations of 100, 75, 50 and 25 mg/l mixed into a DEB

(Diestrol blended- 70% diesel + 20% ethanol + 10% jojoba diesel) fuel and their effect on various diesel engine characteristics. When 25 mg/ l dosage of ANP was used there was a decrease in hydrocarbons and nitrogen oxides emissions when compared with other nanoparticles addition. (Wu et al. 2018) investigated the influence of nanoparticle additives used as fuel catalyst in the blend of diesel- biodiesel, to study the performance characteristics of the engine and reported that BSFC reduced by 6%, emissions of HC decreased by 14.5% and CO reduced by 10% when compared with the biodiesel blend of 10%. (Sivakumar et al. 2018) studied about the impact of ANPs for a fuel blend of 75% diesel-25% pongamia biodiesel inside a diesel engine(single-cylinder) and reported that the B25 blend with 100 ppm alumina doping resulted in a reduction of brake specific fuel consumption by 16.67% and increased brake thermal efficiency to 8.36% when compared to normal B25 blend without alumina doping, which had issues like high evaporation rate, extended flame sustenance, delay in the ignition and high flame temperatures of ANPs. (Charoensaegn et al. 2018) conducted an experiment in a diesel engine with palm biodiesel-diesel-ethanol blend as fuel, and studied about emissions from the engine tailpipe and revealed that the microemulsion biofuels presented an increase in SFC and reduction in nitrogen oxide emissions to an extent. (Soudagar et al. 2018) investigated the impact of nanoparticles on performance characteristics of biodiesel blended diesel engine and reported that incorporation of nano additives resulted in an increase in improvement of thermophysical properties, decrease in emissions from engine tailpipe, better stabilization of air-fuel mixture. (El-Seessy et al.2018) studied the impact of nanoparticle additives blended biodiesel to study the performance characteristics of diesel engine on various loading conditions by adding different ANPs (aluminium oxide nanoparticles) concentrations and reported that at full load condition, there was a decrease in various exhaust emissions like hydrocarbons reduced by 80%, nitrogen oxides by 70% and carbon monoxide reduced by 60%. Ghadikolaei et al. (2019) studied the formation of particulate matter and chemical properties of ternary fuel blend of ethanol-biodiesel-diesel, at various load conditions. They found out that this type of blend has a better impact on DPFE (diesel particulate filter efficiency) and the obtained value of metal elements was 0.7% and ions 1.9% and diesel particulate matter was 85.8%.

Aydin and Yesilyurt (2020) studied the performance characteristics while using the DEE (diethyl ether) and cottonseed oil blend in the diesel engine at various load conditions. Diethyl ether was added to 20% biodiesel- cottonseed blend at various concentrations like 10%, 7.5%, 5%, and 2.5% (on the basis of volume). While adding 10% Diethyl ether to 20% cottonseed- biodiesel blend, it was observed that thermal efficiency was decreased by 17.39% and Brake specific fuel consumption shown an increase of 29.15%. Dogan et al (2020) studied about the diesel engine characteristics which incorporates alcohol as an oxygenated fuel by considering various parameters like sustainability, enviro-economic, exergoeconomic, exergy and energy were analyzed and reported that 20% 10% and 5% 1- heptanol was added (on the basis of volume) to the pure diesel and test results show that SFC is more for 20% 1- heptanol blend of 0. 221 kg.kWh. (Yesilyurt et al.2020) studied the impact of ternary blends of safflower-diesel on the various characteristics of a diesel engine. Through the studies, they concluded that brake specific fuel consumption shows a decrease and brake thermal efficiency shows an increase when ternary fuel blend was used. Addition of pentanol also reduced the emissions of smoke, hydrocarbons and carbon monoxide. Yesilyurt (2020) conducted various tests on diesel engine with a tri-fuel blend of diesel-biodiesel-cooking oil, at various fuel injection pressures of (220 bar, 210 bar, 190 bar, 180 bars, and 170 bar) and reported that BTE has increased considerably at higher injection pressure. Yesilyurt et al. (2020) studied about the blend of four fuels i.e., vegetable oil-alcohol-biodiesel- diesel blend, to analyze the emission, combustion and performance characteristics of a diesel engine. From the results obtained, the author recommends using a 4-fuel blend to achieve better performance in diesel engine in the future. Yesilyurt and Arslan (2019) investigated to study the influence of injection parameters on diesel engine and reported that while using diesel fuel at 190 bar it was found that a maximum of exergy and energy efficiency of 21.27% and 24.5% was obtained.

According to ASTM standards, the chemical and physical characteristics of this ternary fuel is very close to that of conventional diesel fuel. But there was a lack of a decent number of technical literatures on the emission, combustion and performance characteristics of ternary fuel blends for application in a diesel engine. The fuel characteristics of ternary fuel is superior so we can utilize the usage of viable energy resources like biodiesel and bioethanol to its full extent. By this way, we can satisfy the emerging demand for fossil fuels in the present scenario. From this study, a sincere effort has been made to understand the major impacts of ternary fuel at different fuel injection pressure(20 MPa to 50 MPa) on exhaust emissions, combustion and engine performance in a four stroke, single cylinder, common rail direct injection diesel engine (with similar operating conditions) and the obtained results are compared with that of conventional diesel conventional diesel (D100).

Materials And Methodology

Mahua Methyl Ester Preparation

Figure 1 represents the diagram of a biodiesel plant obtained from approved technologies that can be used for making methyl ester. Vegetable oil can be tailored in such a way to decrease its density and viscosity, so that the final product produced will have adequate properties to be used as a diesel engine fuel. The process of using an alcohol to break down the molecules of untreated vegetable oil into methyl in the presence of a catalyst (KOH or NaOH) is known as Transesterification. This process produces glycerin as a by-product which can be used for other purposes. For this process, the catalyst used is KOH at a concentration of 7g/litre dissolved with methanol though powerful stirrings inside a reactor. Next step involves the mixing of the catalyst-methanol mixture with crude mahua oil. Finally, the vigorous stirring of the final mixture for 60 minutes at 60˚C in ambient pressure. After the completion of a transesterification process, two different liquid phases are formed i.e., glycerin and methyl ester. Being in the heavier side, liquid raw glycerin will sink into the bottom after few hours of settling process. After settling, phase separation gets completed in 2-3 hours. Whereas complete settling of methyl ester can take up to 8-10 hours. Methyl ester washing requires two steps. A wash solution made with 1 gm tannic acid per litre of water and vegetable oil (26%) and is mixed to the methyl ester and then emulsified. Stirring is maintained until the methyl ester becomes transparent. The viscosity values of both methyl esters were found to be decreased after the transesterification process, and the value is closer to that of diesel fuel. Methyl ester made through above mentioned process 20% is then blended with plain diesel 80% for preparation of biodiesel blends that can be used in CRDI engine for performing various tests.

Preparation of Ternary fuel blend

As mentioned in the introduction, a TF blend was put forward with 70% diesel, 20% MME and 10% pentanol. Magnetic stirring is done for two hours for 1 liter of this mixture. The obtained blend is named as TF and various tests were conducted according to ASTM standards for deciding various properties like the flashpoint, cetane number, calorific value, kinematic viscosity and density and values are given in Table 1. Cetane number, viscosity and density was decreased by 8.16%, 26.73% and 2.52% respectively, when compared to 100% MME fuel and higher than diesel fuel by 0.83%, 11.97% and 1.43% respectively. Still the properties of TF blend are not a match to conventional diesel fuel.

Table 1. Properties of diesel and ternary fuel blende nano additives

Properties	Fuels	
	D100	TF
Density@20 ^{0}C	830	841
Viscosity@35 ^{0}C	4.1	3.3
Cetane number	45	48
Calorific value (kJ/kg)	42000	41620
Flash point (^{0}C)	53	73
Pour point	3.5	3

CHN Elemental Analysis

A CHN analyzer is used to determine the key biodiesel components, such as nitrogen(N), hydrogen (H)and carbon(C). In a CHN analyzer the biodiesel sample is subjected to oxidative decomposition and consequently, nitrogen reduction takes place along with final products formation such as nitrogen, CO_2, and water. The samples of diesel and blend of MME were analysed with the help of thermo-finnigan CHN. The percentage of carbon in D100 and MME20 was found to be 86.0301% and 84.3253% respectively. So, it is evident from the results that MME has less carbon content when compared to diesel. After combining MME with diesel the MME20 the hydrogen element percentage was 11.8024%. So, it is evident that the percentage of hydrogen content is more in MAHUAME20. Also, it was found that the amount of nitrogen in percentage existing in the diesel and MME20 was found to be 0.18710 and 0.21220 respectively. Table 2 shows the similarity and differences of CHN elements of diesel and MME20

Table 2. CHN element analysis for D100 and MME20 blend

Element	D100	MME20
C (%)	86.0301	84.3253
H (%)	12.0732	11.8024
N (%)	0.1871	0.2122

Experimental Set-up and Methodology

A 4S (4 stroke), Single cylinder, Kirloskar AV1 diesel engine was used to perform the experiments, which was assisted by CRDI system. The power of the diesel engine was rated as 3.7 kW. The injection pressure was kept at the range of 20-100 MPa and speed of the engine was 1500 rpm with different load scenarios. In order to maintain the engine speed according to pressure, fuel injection duration is maintained in between 650-1200μsec. During the initial stage, in order to obtain the baseline data conventional diesel was used in the engine, then, Ternary fuel (pentanol10%+ MME20%+ diesel 70%), were used. Table 3 describes the specifications of the engine. A model of Kirloskar's pump(high-pressure) powered by a motor at run constantly at 1500 revolutions/min. This fuel pump is operated distinctly, to make the injection pressure range of injection wider and more independent of engine speed. In the process of production, the control of pressure is done by an inlet-valve which only allows the required amount of fuel to be pressurized. The pressure adjustments happen by activating spill valves with the help of a signal of extreme frequency. For these adjustments, a controller (16-bit) and an adequate spill flow are required, but since none of them were accessible, the pressure was regulated using a supplementary high-pressure valve. Additionally, a pressure sensor(injection) was mounted on the rail which facilitates the monitoring and controlling of pressure in fuel. In order to offer high pressure data, in between the injector and the rail a pressure transducer(fast-response) was also arranged. Bosch provided the common-rail system which was used on the testbed. A volume of 18 cm^3 with highest pressure upto 100 MPa can be endured by this linear rail having four injector ports. A pressure sensor is fixed on single side of tube. The data recorded by the pressure sensor are sent to the engine ECU for calculation of injection-flow, timing and closed-loop control of the injection pressure. In order to load the engine, ECD (Eddy current dynamometer) was incorporated. The density of smoke was measured using AVL smoke meter. Nitrogen oxide emissions, hydrocarbons and carbon monoxide were measured using AVL five gas analyzer. HRR (heat release rate) and ICP (in-cylinder pressure) are measured with the help of a data acquisition system (dual-core processor interface) as mentioned in the table 4. Figure 2 represents the schematic of the experimental setup.

Table 3. Details of experimental test rig

Make and type	Kirloskar 3.7 kW vertical CRDI engine
Engine type	Automotive (Multispeed)
Stroke length	110 millimeter
Swept volume	625 cubic centimeters
Compression ratio	18.0:1
Torque/Power	30 Nm@2000 RPM, 9 bhp@3000 RPM
Injectors Fuel Injection	Solenoid Common rail direct injection system
Dynamometer	
Make	Power Mag
Type	Eddy current
Load measurement method	Strain Gauge
Maximum load	12-kilogram
Cooling	Water

Table 4. Precision for five gas analysers

Emission apparatus	Range for measurement (PPM)	Measurement principle	Instrument accuracy	%Uncertainty in sampling
NO_x	0(L)- 4000(H)	Electro chemical sensor	±Five (0 to 99(+VE) ppm) ±Five% of mv (Hundred (+VE) to 1999.9(+VE) ppm) ±Ten% of mv (2000 (+VE) to 3000(+VE) ppm)	±0.2
Hydrocarbon (HC)	100(L) -40,000(H)	Electro chemical sensor	< 400 (Hundred to 4000 ppm) < Ten % of mv (> 4000 ppm)	±0.15
Carbon monoxide (CO)	0 (L)-10000(H)	Electro chemical sensor	±Ten (Zero to 199(+VE) ppm) ±05% of mv (200 (+VE) to 2000 (+VE) ppm) ±10% of mv (2001(+VE) to 10000 (+VE) ppm)	±0.2

Uncertainty Analysis

Precise calibration with optimal atmospheric conditions is equally important while using precision measurement devices for reliability. uncertainty analysis gives a broad view of experimental repeatability by counting necessary errors during measurement. In given atmospheric conditions, the process of quantifying performance and emission parameter measurement errors due to the methodology of the experiment, observation accuracy, calibration and instrumentation employed is called the experimental uncertainty analysis. Two major components are identified with uncertainty analysis one of which is repeated measurement random variation and second is accuracy bias. The values of uncertainty are shown in table 3 for gas analyser used and performance parameters. The equation (1) shows the total uncertainty as below.

$$\Delta U = \sqrt{\left\{\left(\frac{\partial U}{\partial x_1}\,\Delta X_1\right)^2 + \left(\frac{\partial U}{\partial x_2}\,\Delta X_2\right)^2 + \ldots + \left(\frac{\partial U}{\partial x_n}\,\Delta X_n\right)^2\right\}} \qquad (1)$$

$$Overall\ uncertainty\ of\ the\ experiment\ =$$

$$\sqrt{(1)^2 + (0.2)^2 + (1.0)^2 + (0.2)^2 + (0.2)^2 + (0.2)^2 +}\,(0.2)^2 + (1.0)^2 + (0.15)^2 = \pm 2.15\%$$

The evaluation of uncertainty values of each equipment was conducted, which established the experimental uncertainty (current) to be ±2%. This value is obviously within the acceptable uncertainty range i.e., less than ± 5%.

Results And Discussion

The working of diesel engine aided by common rail direct injection system with fuel as Ternary fuel (pentanol10%+ MME20%+ diesel 70%), blends and was observed to be pretty clean for the entire rated load and varying pressure during fuel injections of 22-88 MPa. SFC, BTE and emissions (nitrogen oxide emissions, HC, CO) and density of smoke are plotted against load. With the available data regarding combustion, HRR and cylinder pressure was plotted against crank angle.

Effect of Fuel Injection Pressure on Engine Combustion Characteristics

Cylinder Pressure

Figure 3 illustrates the variation of inside cylinder pressure of ternary fuel w.r.t to crank angle at various injection pressures. It is observed from the plot that pure diesel at pressure of 51.62 bar is at the least point, whereas the maximum cylinder pressure is observed for TF50 at 60.10 bar because of the shorter ignition delay. Pentanol’s presence in ternary fuel helps the oxygen molecules present in it for effective combustion with improvement in cylinder-pressure. To sustain burning in the main combustion phase and for the complete combustion of the fuel during the pre-combustion phase, higher content of oxygen in ternary fuel is enough. It is evident that TF50 has 0.91% higher peak pressure when compared with the conventional diesel fuel. While testing fuel with during running of engine at no load and partial load scenarios similar tendencies were seen. The fuel-air combination generation is fairly constant which results in increased pressure when the cetane number is improved and viscosity of fuel remains higher. It is observed from the plot that the with an increase in the injection pressure from 20Mpa to 50 MPa cylinder pressure also increased. For TF20 cylinder pressure was found to be 52.68 bar, for TF30 it is 55.273 bar and for TF40 it is 58.112 bar. Reason for the same could be the production of the better atomization thereby reducing physical delay. Cylinder Pressure of TF50 is found better, which is 60.10 bar measured amongst various fuel injection pressures and it is 4.39% greater from TF20.

Figure 3. Variation of in-cylinder pressure against crank angle for different fuel injection pressure

Heat Release Rate

Figure 4 illustrates the variation of heat release rate w.r.t to crank angle for different fuel injection pressure at full load condition. When compared to other fuel injection pressures, heat release rate of D100 is observed to be as 110.36 kJ/m^3deg this is due to the fact that the accumulation of diesel fuel at the primary combustion phase which is in the premixed stage. Due to the better thermal physical characteristics of ternary fuel resulting in the advancement of combustion process as mentioned in the open literature. It is observed from the plot that the with an increase in the injection pressure from 20MPa to 50 MPa heat release rate also increased. Combustion phasing of ternary fuel advances and heat release rate reaches its peak as the injection pressure increases from 20Mpa to 50MPa because of ignition delay shortening through improved fuel-air mixing. Because of improved atomization of injected fuel, higher dispersion, disintegrate length and average diameter of the fuel droplet, ignition delay period decreases to an extent when injection pressure is increased. Maximum heat release rate of 126.89 kJ/m^3deg is observed in TF50 whereas heat release rate of 120.33 kJ/m^3deg is observed at fuel injection pressure of TF20.

Effect of Fuel Injection Pressure on Engine Performance Characteristics

Brake Thermal Efficiency

For ternary fuel (pentanol10%+ MME20%+ diesel 70%) with different fuel injection pressure from 20 MPa to 50 MPa, it was evident that the BTE has increased with an increase in load as illustrated in the figure 5. The brake thermal efficiency of ternary fuel at FIP of 50MPa (TF50) was much greater when compared with other FIPs and also conventional diesel. Brake thermal efficiency of diesel is minimum (at all loads) with lower levels of viscosity and density. Brake thermal efficiency at all loads is seen to increase because of the presence of pentanol in ternary Fuel. This is mostly due to sufficient oxygen molecules in pentanol resulting in better combustion. As brake thermal efficiency of ternary fuel is still lower, enhancement in the same can be sought with an increase of fuel injection pressure. It is observed from the figure that with an increase in the FIP an increase of 1.58%, 1.62%, 2.34% and 4.39% was observed TF20, TF30, TF40 and TF50in brake thermal efficiency. Simultaneously, as the evaporation rate is increased and physical delays are reduced which leads to improved BTE along with an increase in combustion efficiency. In comparison with TF30 and TF40, better thermal efficiency is observed at TF50 at various engine loads. These results are in accordance with the increase in FIP in the ternary fuel blend with the increased thermal efficiency as mentioned in the open literature.

Specific Fuel Consumption (SFC)

Figure 6 represents the variations in BSFC (specific fuel consumption) for ternary fuel with different fuel injection pressure and conventional diesel with load. In correspondence to increase in the heating value, BSFC of ternary fuel is also expected to increase. Comparing the properties, ternary fuel has got a higher heating value than diesel fuel. As compared to diesel fuel, SFC while fuelling with the ternary fuel is increased, which can be seen in figure 6 and this states agreement with many literatures [24-28] as well. Figure 6 also shows the increase of injection pressure along with reduction of consumption of specific fuel. Atomization takes place as fuel droplet diameter decreases because of increase in the injection pressure which leads to better combustion. At a FIP of 20MPa, conventional diesel has higher BSFC than ternary fuel at different FIP. A substantial lessening of around 7.5% was observed in BSFC of ternary fuel at 50MPa when compared with ternary fuel of 20MPa. The BSFC becomes 0.34, 0.33 and 0.31 and 0.30 kg/kW-hr for TF20, TF30, TF40 and TF50 respectively for different fuel injection pressure at maximum load.

Effect of Fuel Injection Pressure on Engine Emission Characteristics

Carbon monoxide Emissions

Figure 7 illustrates the variation of carbon monoxide emissions for ternary fuel for different fuel injection pressure, clearly indicates that in comparison to plain diesel, ternary fuel blends outperforms it by emitting a significantly lesser quantity of CO. This reduction is due to the combustion enhancer, pentanol which amplifies the combustion process. Apparently, due to the presence of high oxygen quantity, the rate of conversion from carbon dioxide to monoxide gets accelerated while using ternary fuel in an engine. Initial decrease of CO emission at inferior loads up to 30% and significant increase for the ternary fuel is observed. Due to excess oxygen present in methyl esters, combustion is relatively smoother than diesel [30]. It is observed from the figure that for ternary fuel at fuel injection pressure of 20 MPa, 15.78% decrease in CO emission is reported in comparison with conventional diesel. By-product of incomplete combustion is called carbon monoxide which is generated from the incomplete oxidation of compounds containing carbon. When there is insufficient oxygen to make CO_2, carbon monoxide is produced. The condition wherein CO emission appears due to rich-mixture and the pressure surge happens during injection of fuel which in turn directs the mixtures to progress towards lean. Here, CO emission is decreased to 22.24% when there is an increase in FIP of 50MPa.

Hydrocarbon Emissions (UHC)

At different fuel injection pressure, the variation in emissions of unburnt hydrocarbon (UHC) against engine load is presented in figure 8. To determine the emission behaviour of the engine, UHC is also an important limitation. At all the engine loads, UHC emission is observed to be highest in conventional diesel as compared to ternary fuel which emitted 6.84%,10.36%,11.31%, and 9.49% (TF20, TF30, TF40 and TF50) of unburnt hydrocarbons. This trend matches with CO emission of ternary fuel with respect to plain diesel. Increase in the load affects the UHC emission because of high air-fuel mixture generation in wall films and crevices (cold quench areas) and plenty of available fuel in the combustion zone. Here, we can conclude that hydrocarbon emission further decreases as pressure during injection increases.

Nitrogen Oxides

The variation of pure diesel, ternary fuel blended with nanoparticle additives and MME20 against load for NO_x emission is illustrated in figure 9. NO_x generation is a sophisticated process. A number of factors are responsible for NO_x formation like working conditions, response time, combustion temperature, features of engine design, fuel properties etc. From the plot, it can be observed that diesel produced lesser NO_x emissions than ternary fuel. The reason could be the oxygen molecule presence which amplified the combustion process and thereby raising the combustion chamber temperature. Due to very high temperature inside the cylinder resulting through better combustion, NO_x emissions raised for ternary fuel by 12.46% when compared with diesel when the load is increased to maximum. However, this property of high oxygen content helps in improving combustion and HRR in presence of high temperature inside cylinder but it’s a threat to our environment as well. This NOx generation further increases due to its bulk modulus and injection of fuel happening earlier than usual. Nitrogen and oxygen combinedly yield high quantity of Nitrogen Oxide at high temperatures due to better combustion.

Smoke Opacity

In Figure 10, for the different fuel injection pressures of the smoke opacity variation in relation to engine load is illustrated. Highest smoke emission is observed in diesel for all the load conditions as compared to ternary fuel. Excess accumulation of fuel in the cylinder, deficiency of oxygen in the combustion rich areas and poor atomization result in the formation of smoke in CI engines which is mostly due to partial combustion. Thus, it means that the low smoke emissions found in ternary fuel are due to better fuel oxidation inside the combustion chambers present near the fuel-rich zones. Smoke level is further reduced with the increment of pressure during injection of fuel. Further, smoke emissions were seen to be nominally reduced by 6.15%, 6.92%, 5.37% and 5.12% at full load for TF20, TF30, TF40 and TF120 respectively. The lower smoke emission is probably due to the lower delay period due to which before ignition, surplus fuel is collected inside the cylinder making sure that combustion rate is high enough and better fuel-air mix is facilitated.

Ignition Delay

The delay period, commonly known as the ignition delay period is the time period from the start of fuel injection to the initiation of combustion. It also indicates the chemical as well as the physical delay of the fuel. The ignition delay suggests fuel mixing and atomization at the final stage, while the full pre-combustion process is shown at the initial stage. Depending on engine load for different fuel injection pressures the change in ignition delay is depicted in figure 11. The highest ignition delay is observed in the convention diesel at all loads. But for lower loads TF30 and TF40 showed a similar delay profile. The reason behind this was mainly due to the viscosity, density and better fuel mix rate. The next blend having lower delay period was TF20 due to its low compressibility factor, high cetane number and biodiesel composition. The reason behind low delay period is attributed to better fuel atomization through high surface tension and calorific range of the blend.

Trade-off (BSFC- BTE- NOx)

The detrimental effects of soot and NO_x are well known to everyone. They cause a plethora of respiratory illness and degrade the environment by causing global warming through smog formation. Furthermore, a fuel which is consumed in lesser quantity by the engine is one of the factors to choose a fuel; another reason being the depleting fuel reserves. Thus, to get a clearer picture, a trade-off study is required for comparing emission and performance of engines using various fuels with respect to SFC, brake thermal efficiency and NO_x emission. It also gives scope for further explanation of intrinsic issues regarding the above. Figure 12 shows the 20% to 100% load trade-off for different combinations of ternary fuel (pentanol10%+ MME20%+ diesel 70%) with different injection pressures (TF20, TF30, TF40 and TF50). It can be noticed clearly that the trade-off shifts to the extreme left corner (minimum fuel consumption) from extreme right corner (maximum fuel consumption). From the graph, the TF50 is seen to push the trade-off to a high-NO_x emission zone and BTE with a reduction of BSFC. Ternary fuel operation reduces the equivalent BSFC along with NO_x emission. Of the other blend, ternary blend produces lesser NO_x and more BTE. When the load is increased to 40%, the TF50 blends the smoke opacity and equivalent-BSFC reduction is seen which is indicated through the shifting of trade-off zone near to origin. Based on the trade-off pattern for the fuel sample considered, the following results can be concluded (1) Whenever the percentage of ternary fuel blended with iron oxide additives got increased, it is seen that BSFC decreases but when BTE rises NOx also goes up (2) On the other hand, TF50 shows high emission of NOx and BTE but relatively low BSFC as portrayed in the top area of the graph (3). Interestingly, TF40 shows the optimum trade-off zone with higher BTE and lower BSFC and lowest NOx emission from the current study.

Conclusions

The present work is focussed on the influence of high fuel injection pressure on ternary fuel and D100 are studied for their effect on engine emission, performance and combustion characteristics. Following conclusions are drawn based on extensive experimental study.

 TF (Ternary fuel) is obtained by mixing 10% pentanol, 20% MME biodiesel and 70% diesel together. High NO_x and BSEC were observed for ternary fuel than conventional diesel.

 Due to poor mixing characteristics, time for combustion of ternary fuel was higher than the conventional diesel in current research. With an increase in the FIP, cylinder pressure also increased which also led to increase in heat release rate.

 BSFC drastically reduced to 7.5% when the pressure during injection of fuel was increased from 20 to 50MPa. With an increase in FIP, brake thermal efficiency also increased.

- As compared to D100, ternary fuel showed lower CO, HC and smoke. Also, when the pressure during injection of fuel was increased to 50MPa from 20 MPa, CO, HC and smoke emissions were further reduced.

- It was concluded that ternary fuel usage in C.R.D.I. diesel engines with a fuel injection pressure of 50 MPa leads to better thermal efficiency(BTE) and reduction in harmful gas emissions.

Declarations

Author contributions

Jatoth Ramachander: Conceptualization, methodology, writing, review and editing; Santhosh Kumar Gugulothu: Formal analysis and investigation, writing original draft and preparation; Gadepalli Ravikiran Sastry: Supervision; Burra Bhasker: Supervision.

Data Availability: All data generated or analyzed during this study are included in this article.

Compliance with ethical standards

The present study work was not conducted on human or experimental animals where national or international guidelines are used for the protection of human subjects and animal welfare.

Ethical Approval: Not applicable

Consent to participate: Not applicable

Consent for publication: We confirm that the manuscript has been read and approved by all named authors and that there are no other persons who satisfied the criteria for authorship but are not listed. We further confirm that all the authors listed in the manuscript has been approved by all of us.

Competing interests: The authors declare that they have no competing interests.

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Figures

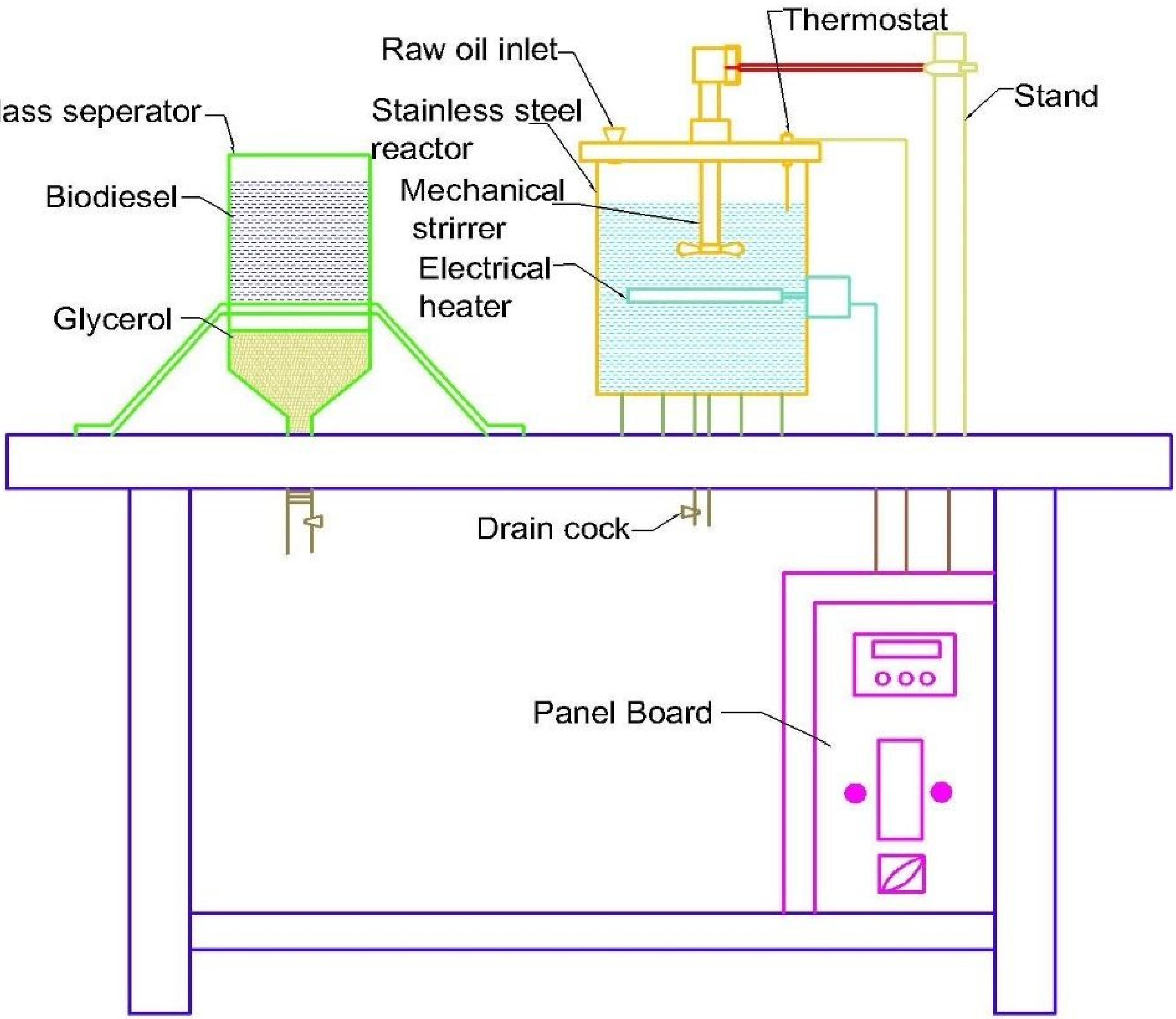


Figure 1

Transesterification process (Biodiesel plant)

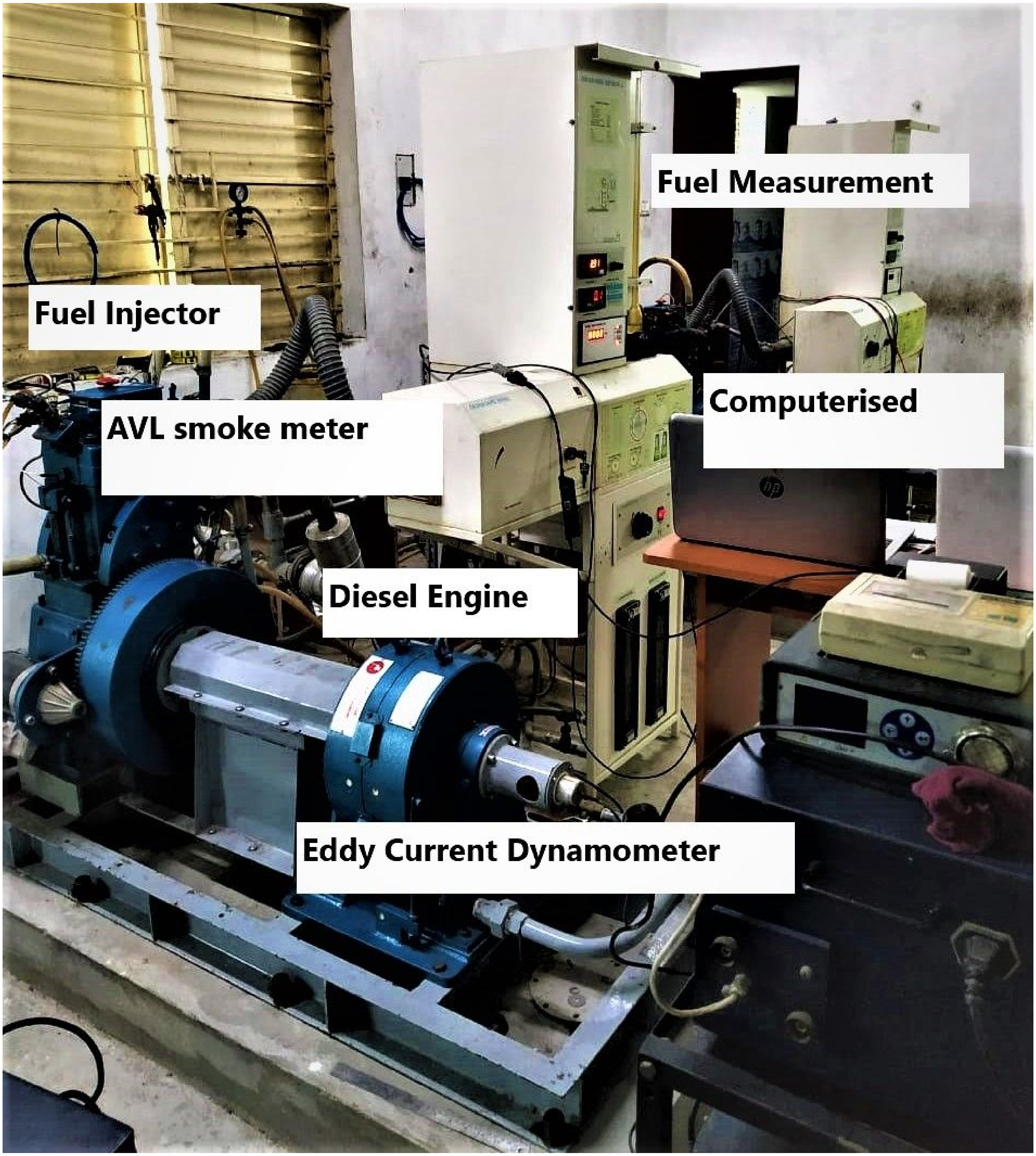


Figure 2

Schematic of Experimental layout

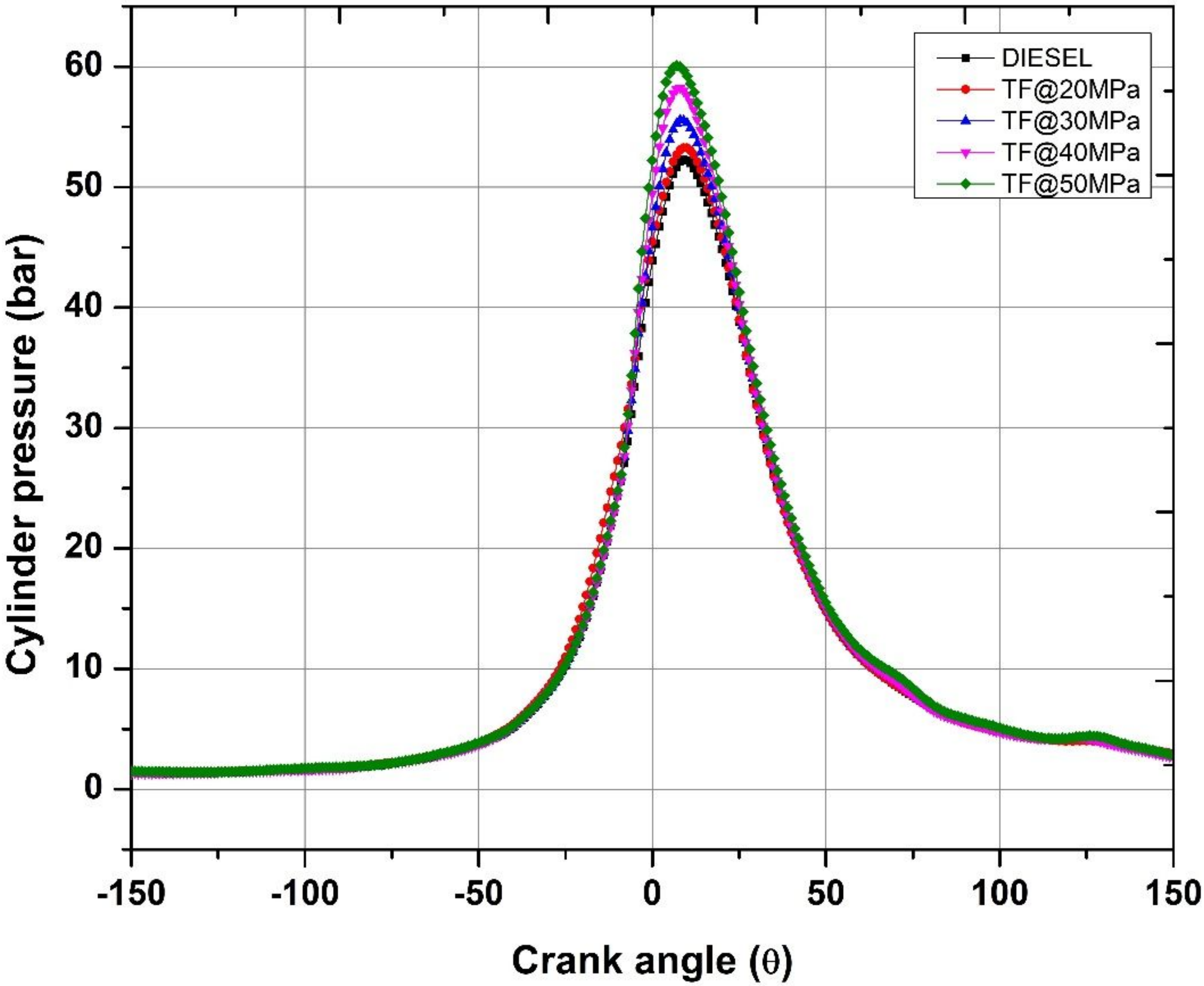


Figure 3

Variation of in-cylinder pressure against crank angle for different fuel injection pressure

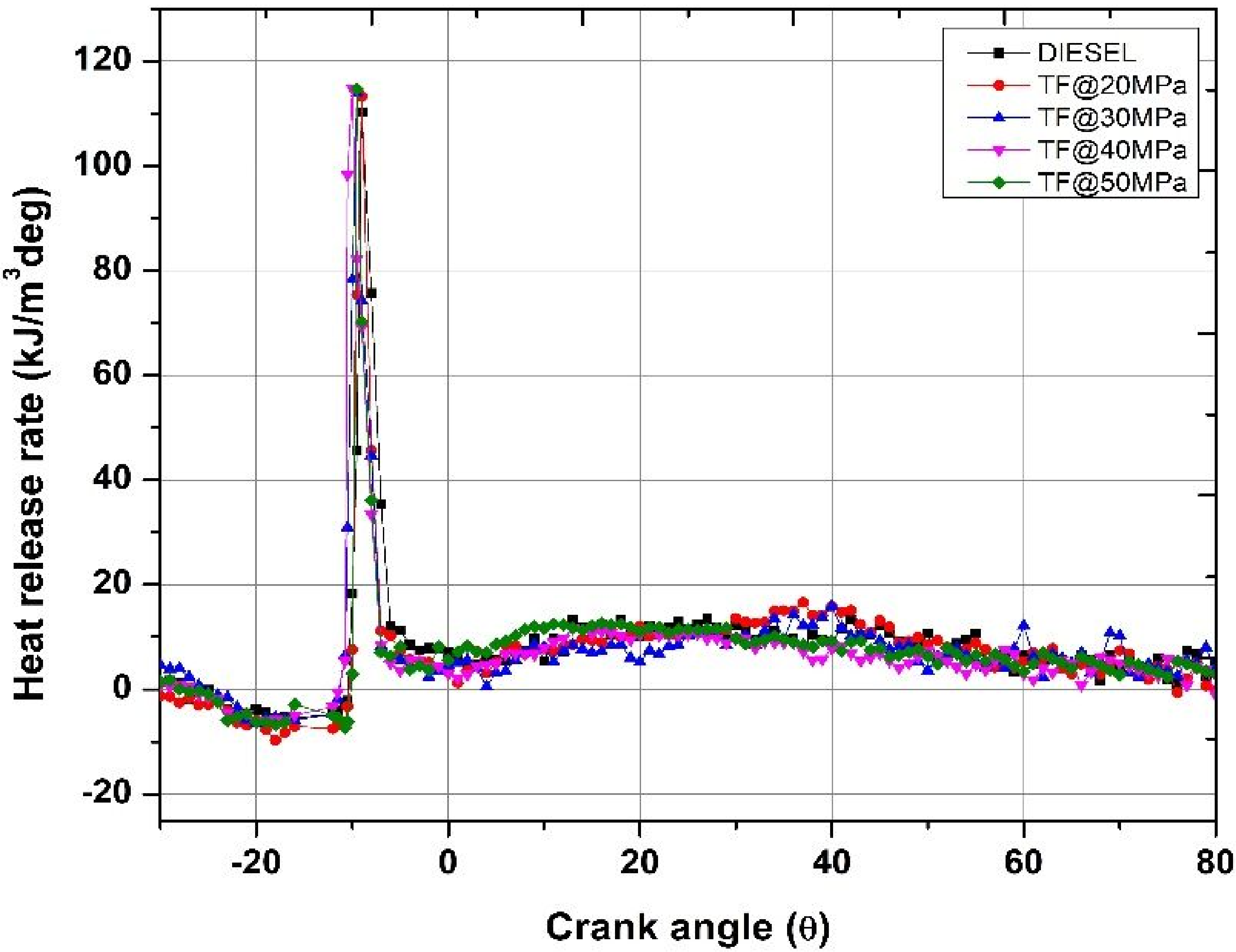


Figure 4

Variation of heat release rate against crank angle for different fuel injection pressure

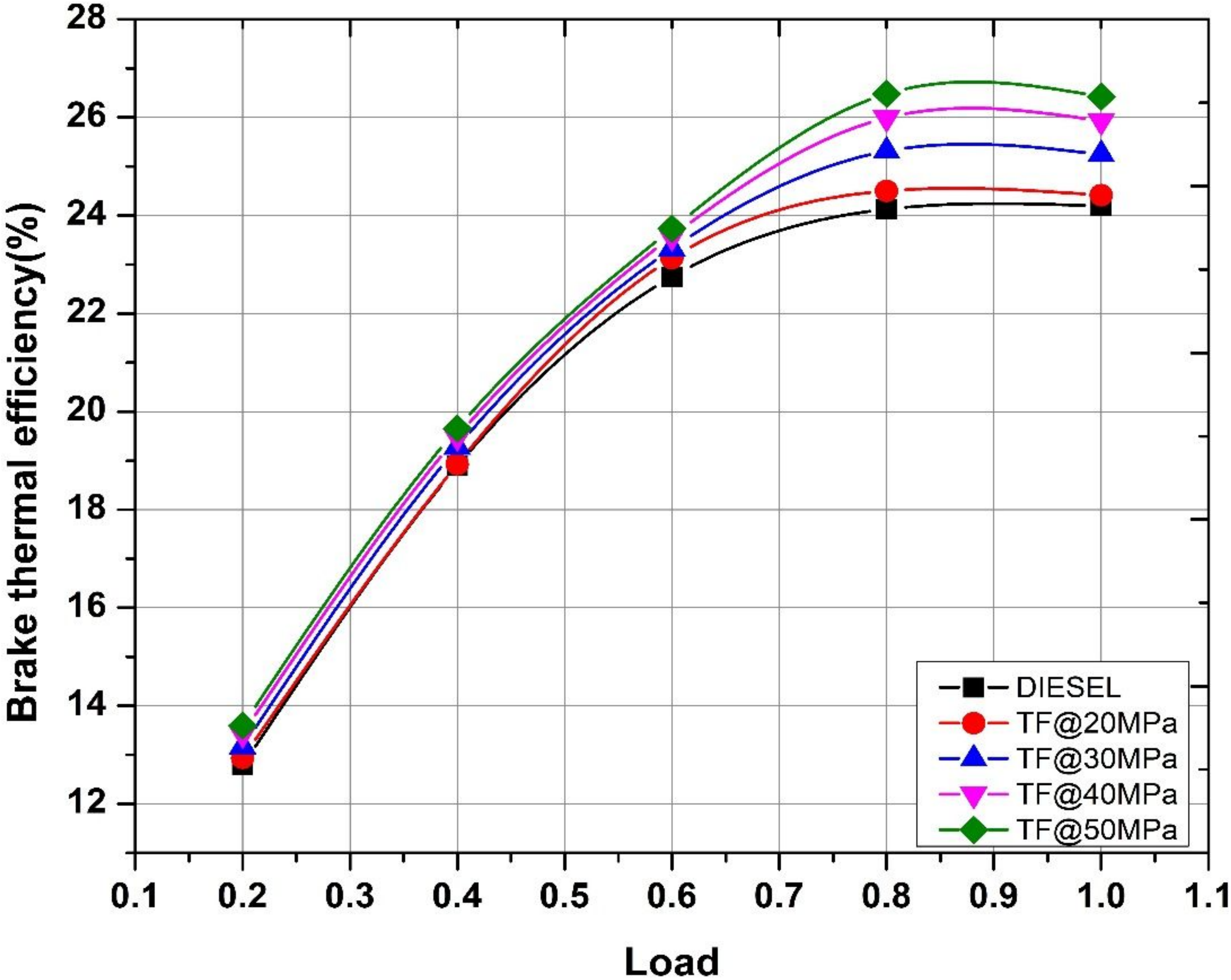


Figure 5

Variation of Brake Thermal Efficiency against load for different fuels

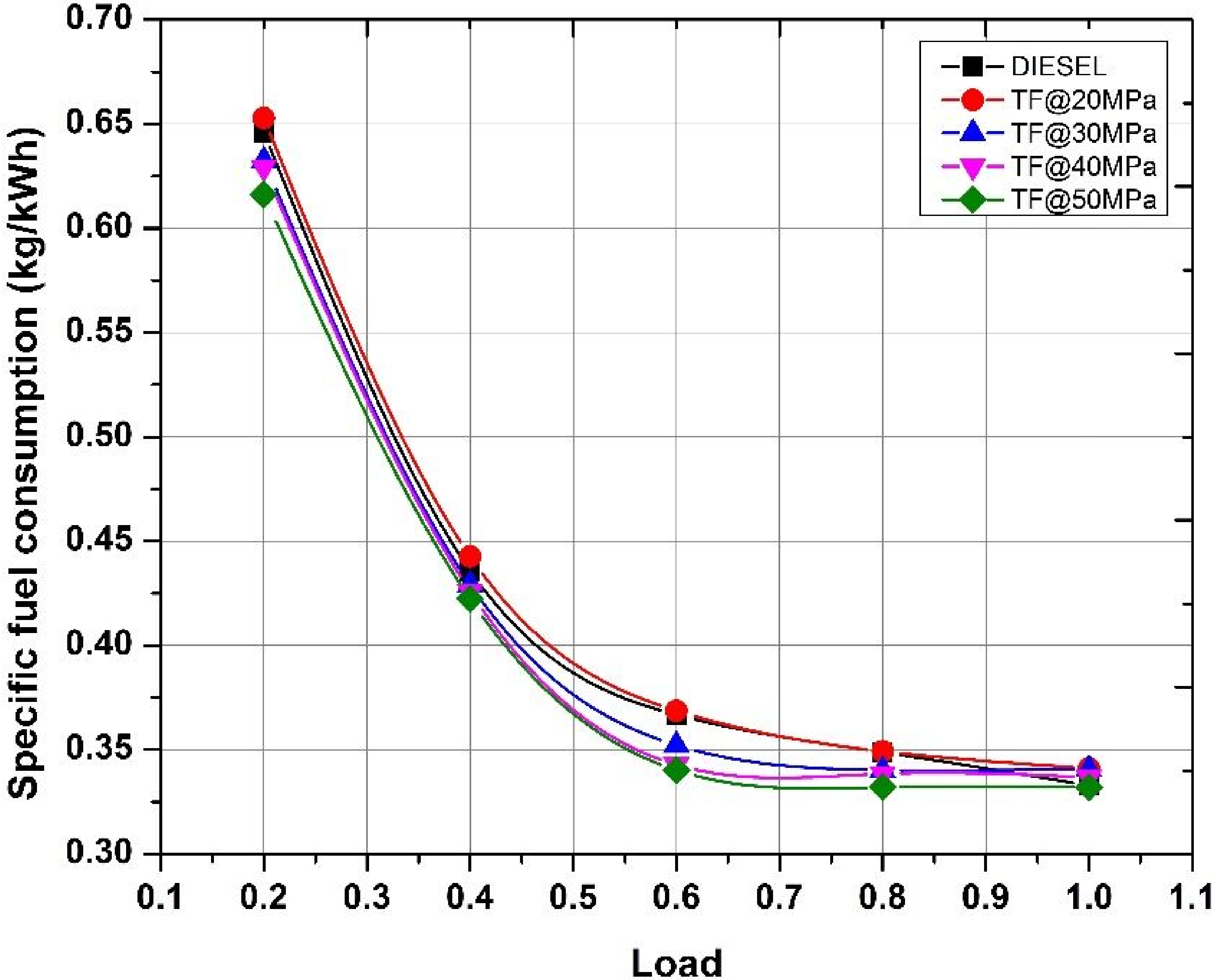


Figure 6

Variation of Brake specific fuel consumption against load for different fuel injection pressure

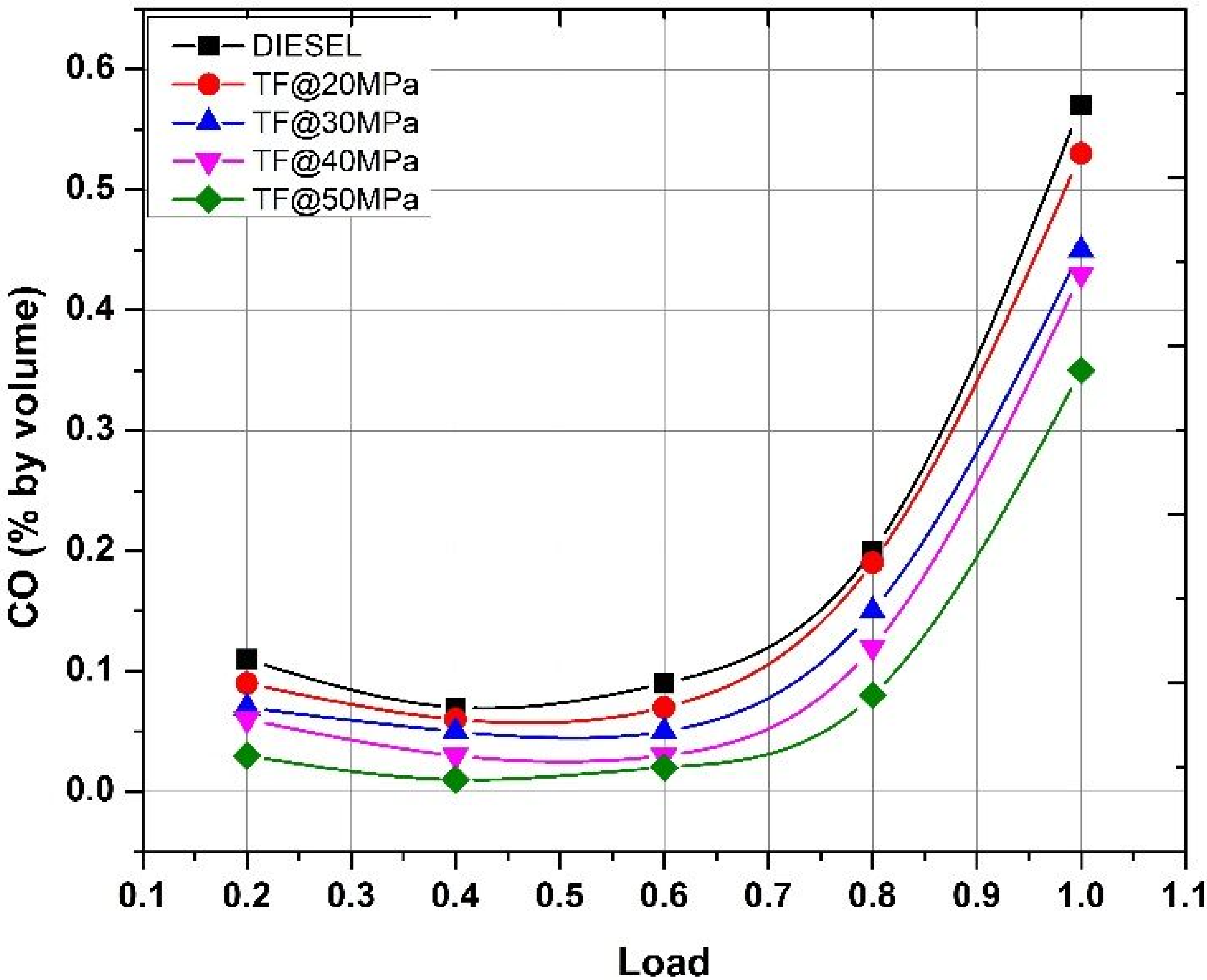


Figure 7

Variation of carbon monoxide emissions against load for different fuel injection pressure

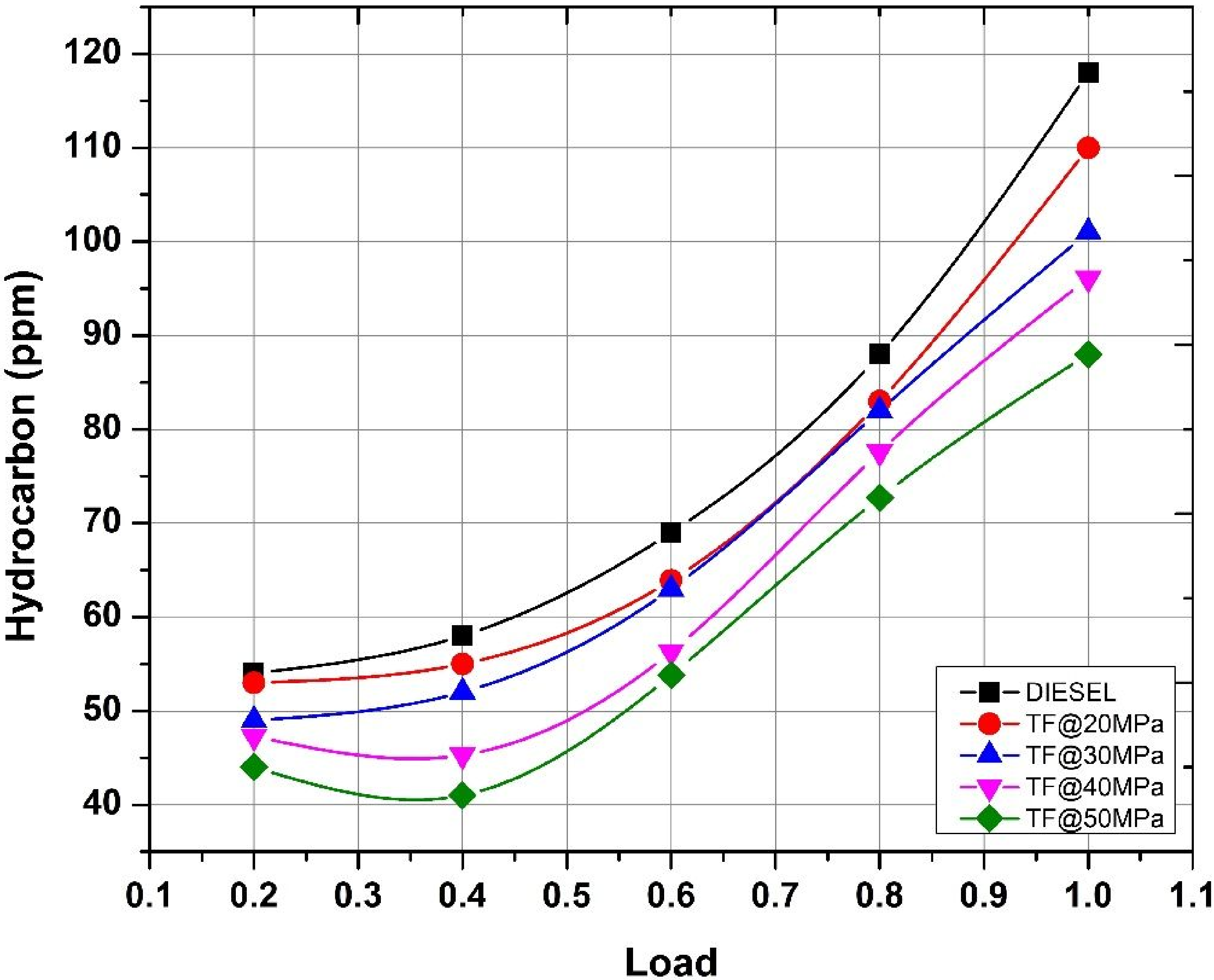


Figure 8

Variation of unburnt hydrocarbon against load against different fuel injection pressures

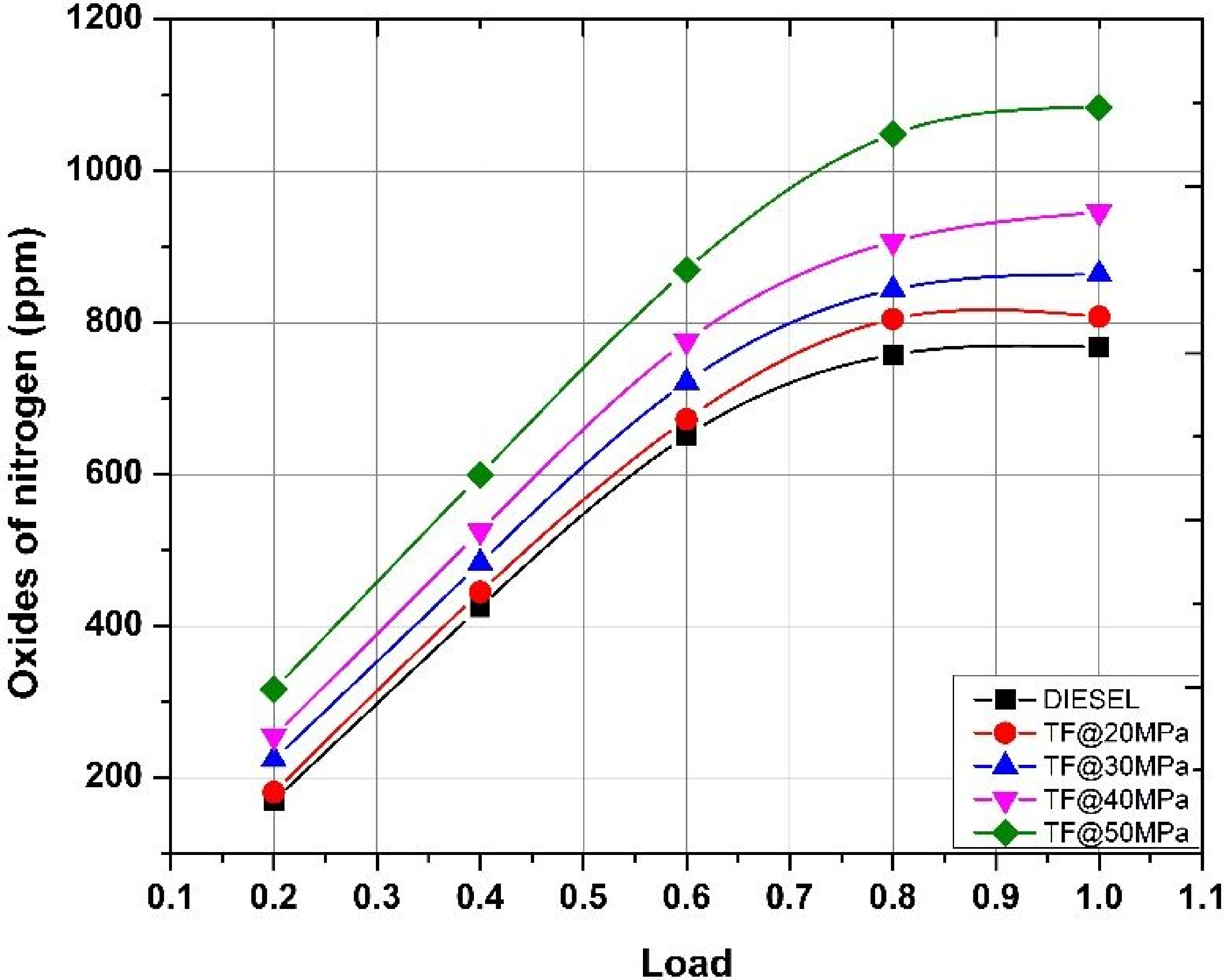


Figure 9

Variation of oxides of nitrogen against load for different fuel injection pressures

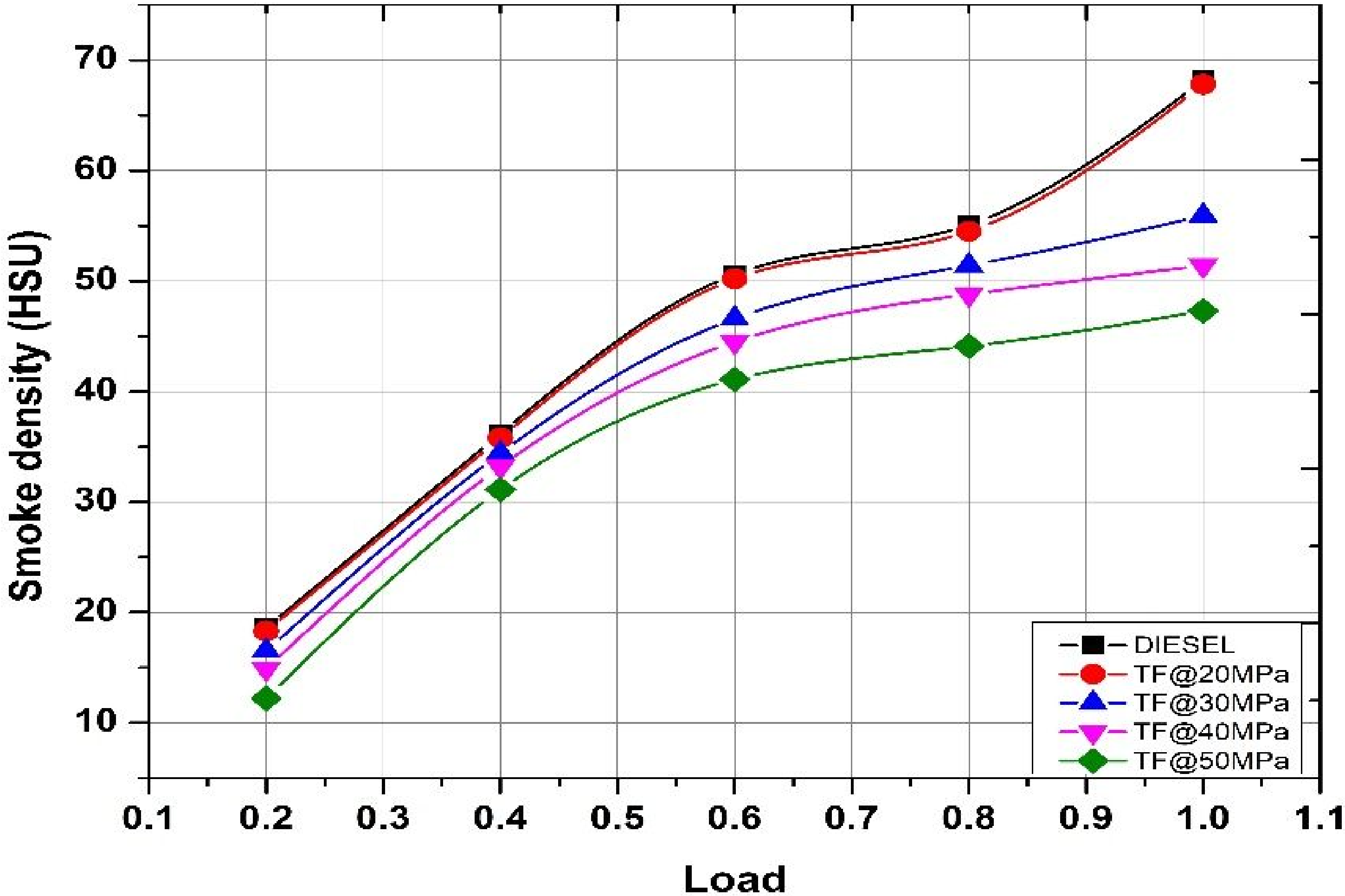


Figure 10

Variation of smoke opacity against load for different fuel injection pressures

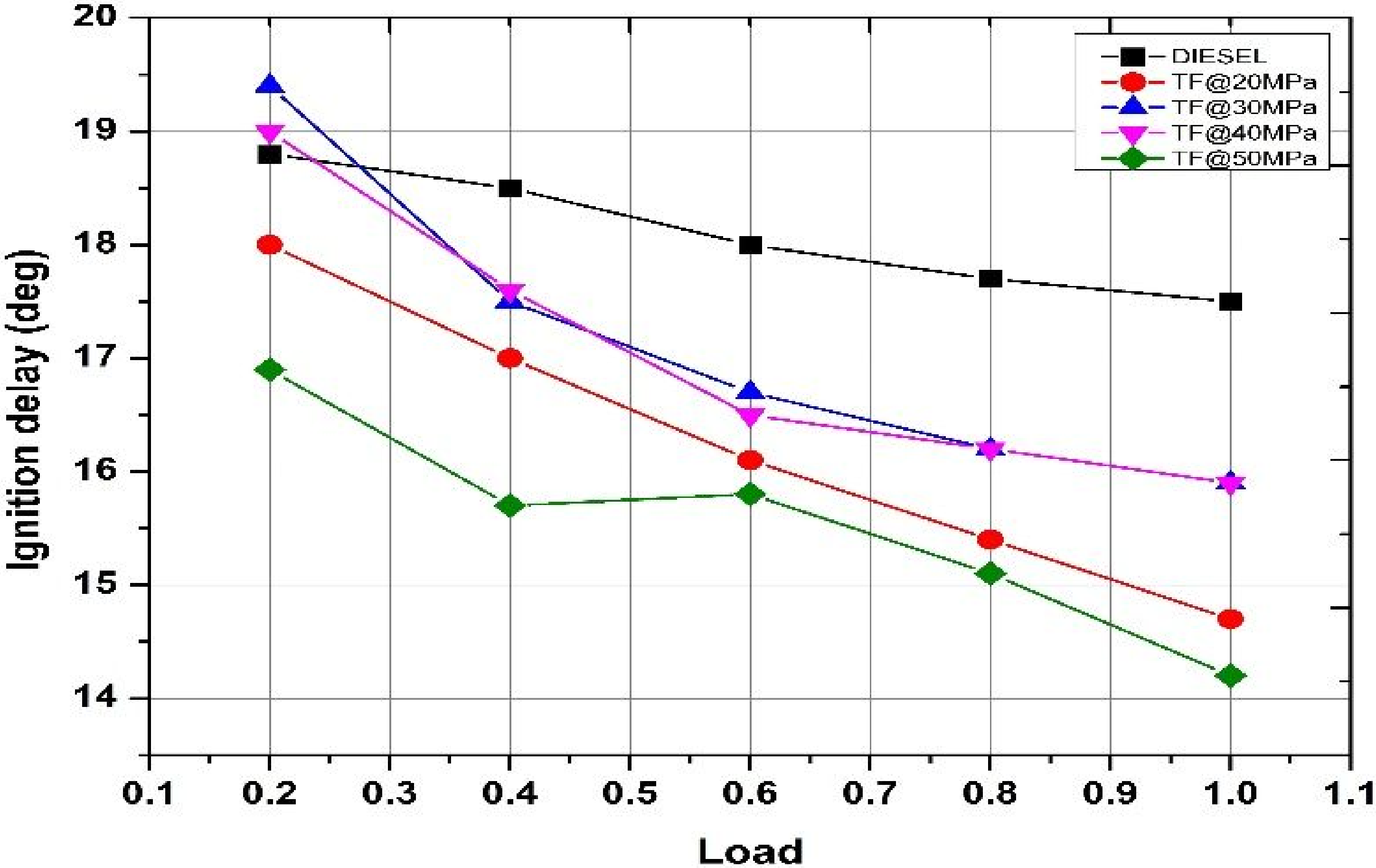
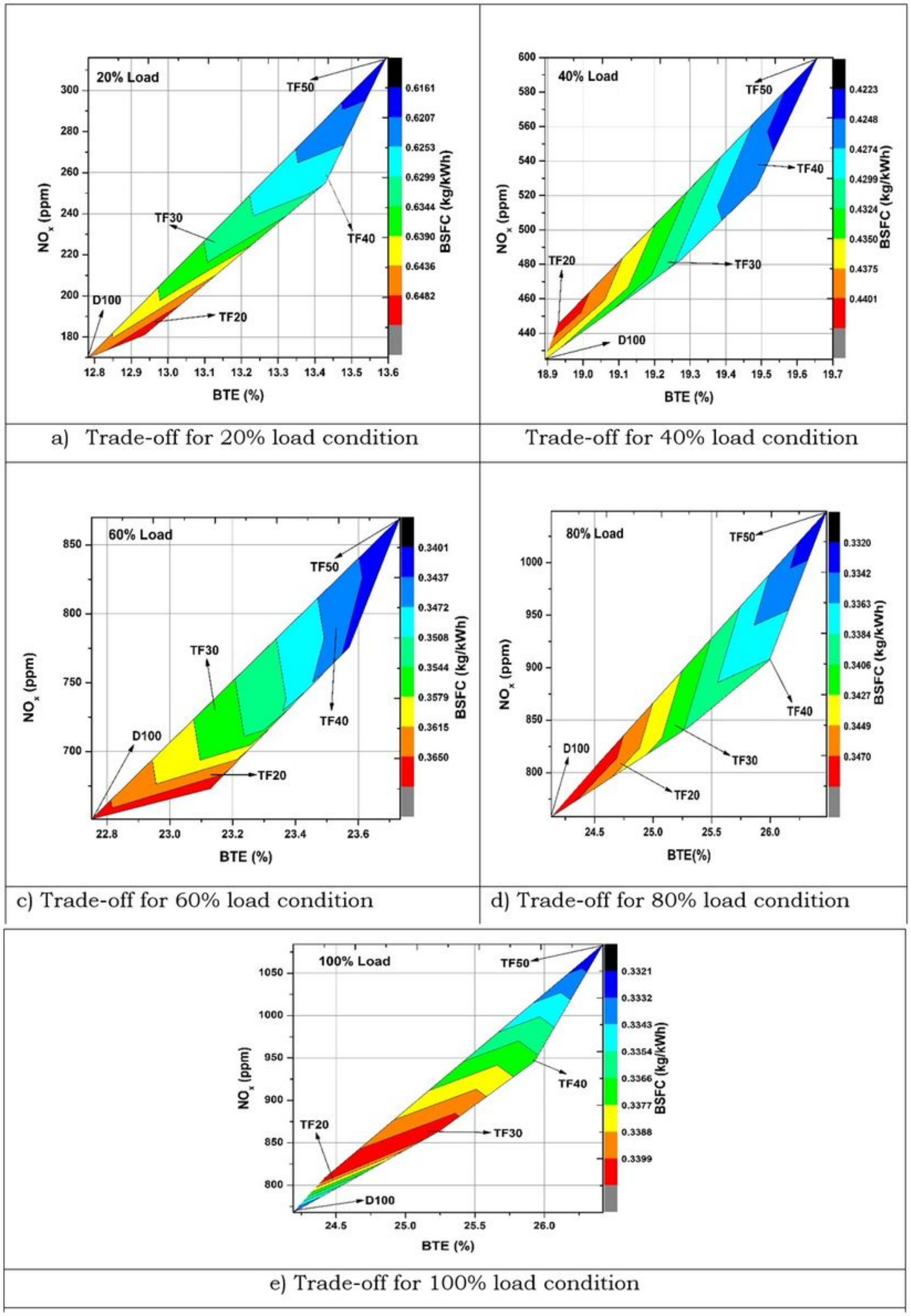


Figure 11

Variation of ignition delay against load for different fuel injection pressures



a) Trade-off for 20% load condition

Trade-off for 40% load condition

c) Trade-off for 60% load condition

d) Trade-off for 80% load condition

e) Trade-off for 100% load condition

Figure 12

Trade-off study (BSFC- BTE- NOx)