Combustion, Performance and Emission Characteristics of a DI Diesel Engine Fueledwith Non-Petroleum Fuel: A Study on the Role of Fuel Injection Timing

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ABSTRACT

Earlier investigations by the authors revealed that a blend of 80% Jatropha methyl ester (JME) and 20% Tyre pyrolysis oil (TPO) referred to as JMETPO20 blendexhibited a better performance and lower emissions compared to other JMETPO blends [1]. Being a fuel derived from a non-petroleum source, the original injection timing of diesel engine may not be suitable for the blend. In this study, the influence of the injection timing on the combustion, performance and emission characteristics of a single cylinder, four stroke, air cooled, constant speed, direct injection (DI), naturally aspirated diesel engine has been experimentally investigated, when theengine was run with theJMETPO20 blend. The original injection timing was altered by adjusting the number of shims fitted under the plunger in the pump, by addition or removal of shims.In addition to the original injection timing of23 °CA bTDC, other injection timings at which the study was carriedout were20, 21.5, 24.5 and 26°CA bTDC.The results indicated that the blend gave a better performance and lower emissions when operated with an advanced injection timing of 24.5 °CAbTDC as compared to other injection timings. Atthe advanced injection timing of 24.5°CA bTDC, the maximum cylinder pressure was found to behigherby about 2.73bar with alonger ignition delay, than that in case of the original injection timing at BMEP of 5.6 bar.Further, thebrake specific energy consumption decreased by about 7.1% compared to that of the original injection timing at BMEP of 5.6 bar. The carbon monoxide, hydrocarbon and particulate emissions were alsofound to be reduced by about 14.2%, 13.26% and 9.3% respectively.

Keywords: Diesel engine; Alternative fuel; Performance; Emission; Injection timing; Combustion characteristics

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1. INTRODUCTION

India is one of the fastest developing countries in the world with a stable economic growth, which multiplies the demand for petroleum fuels manifold. It was reported that in theyear 2011, India was the fourth largest energy consumer in the world after the United States, China, and Russia [2]. To meet the ever growing energy requirement, it depends mainly on imported crude oil due to lack of fossil fuel reserves, and this has a great impact on the economy. Therefore, India has to consistently look for an alternative to meet the future energy demand.

Various alternative fuels for diesel engines have been explored by many researchers over the past few decades [3-6]. Among the various possibilities, biodiesel is the topic of interest today, because it is renewable, oxygenated biodegradable, non-toxic, and environment friendly [7-8]. Moreover, in many countries, agricultural land is abundantly available where biodiesel can be produced at low cost. Biodiesel is a fuel composed of mono-alkaline esters of long chain fatty acids that are obtained from triglycerides such as vegetable oil, animal fat or algae. Numerous research works have been documented in the past on the utilization of biodiesel in compression ignition (CI)engines, both stationary and mobile [9-11].It can be directly used as a fuel in diesel engines without any major engine modification,and it gives almost equal fuel efficiency and lower particulate emission compared to conventional diesel. The demerits of a biodiesel fueled engine include issues of poor cold flow properties, higher viscosity and higher emission of nitrogen oxides compared to a diesel fueled engine [12]. It is reported that for every 10% increase of biodiesel content in the diesel-biodiesel blend, the engine will produce 1% morenitric oxide (NO) emission [13]. This is the major issue related to most biodiesels from the emission point of view. In India, the biodiesel production has been initiated in an organised manner in the last two decades. Several researchers in India have tried different non-edible feed stocks such as Jatropha curcas, Pongamia pinnata, Madhuca indica and Linseed etc. for the production of biodiesel[14-17]. Among these, Jatropha curcas and Pongamia pinnata are considered as potential feedstocks, because of their higher biodiesel yield. Initiatives were taken to produce different non-edible oil feedstocks for promoting biodiesel production in India [18]. However, the availability of seeds is limited, discouraging the use of biodiesel. The debate over the ethical and practical consideration of replacing 'mineral' diesel with biodiesel has been lengthy as well as contentious[19]. The search for alternative hydrocarbon sources to be used as extenders of biodiesel and to add to this replacement still continues.

In recent past, apreliminary research work was carriedout by the authors to study the effect of blending tyre pyrolysis oil (TPO) with a fuel, whose cetane number is greater than that of diesel. Jatropha methyl ester (JME) with acetane number marginally higher than diesel was blended with TPO in different proportions. The content of TPO in the blend was varied from 10% to 50% with a regular interval of 10% on a volume basis. The blends were denoted as JMETPO10, JMETPO20, JMETPO30, JMETPO40 and JMETPO50, where the numeric value represents the percentage value of the TPO in the Jatropha methyl ester tyre pyrolysis oil (JMETPO) blend.The experiments were conducted in a single cylinder, four stroke, air cooled, direct injection (DI) diesel enginewith a rated power of 4.4 kW at 1500 rpm, to study the combustion, performance and emission characteristics,when the engine was fueled withdifferent JMETPO blends. The test results confirmed that, the JMETPO20 blend exhibited reasonably better performance and lower emissionsthan those by other JMETPO blends. The brake thermal efficiency (BTE) for the JMETPO20 blend was equal to that of diesel at full load. Further, the carbon monoxide(CO), hydrocarbon(HC)emission and smoke opacityalsoreducedby 9.1%, 8.6% and 26% respectively, compared to those in case of diesel at full load[1].

Generally, CI engines are designed to operate only with diesel. For other fuels, certain operating parameters of the engine have to be optimized,in view of the combustion,performance and emission characteristics[20].It is important to note that the engine behaviour is predominantly affected by the fuel-air mixture supplied to the diesel engine. The fuel quantity is governed by the fuel injection rate, injection timing and nozzle geometry. Besides, injection timing plays a vital role in the performance and emission characteristics of a diesel engine, as the pressure and temperature change significantly as the piston approaches the top dead centre (TDC)[21].

Research works aimed to study the effect of injection timing on the combustion, performance and emission behaviour of a DI diesel engine fueled with different alternative fuels, havebeen documented in the recent past [22-27]. Most of thesestudies reported that advancing the injection timing of a DI diesel engine fueled with high viscous (viscosity higher than that of diesel) fuels exhibitsa higher heat release rate (HRR) in the premixed combustion phase [28]. As a result of this higher HRR attained in the premixed combustion phase, the power output and the thermal efficiency were observed to be higher than the original injection timing. It was also reported that the advancement in the injection timing resulted in higher NO

emissionand reduced smoke emission for most of the fuels [29].On the contrary, a shorter ignition delay, lower peak pressure and temperature and lower heat release rate were reported, for retarded injection timing [30]. Lower NO emission with the penalty of smoke emission was also reported with retarded injection timing of high viscous fuels [31]. The reason mentioned was that, as the maximum HRR was observed to be closer to the TDC, the maximum pressure thrust on the piston to develop an effective power, was found to be shifted much away from the TDC.At retarded injection timing, power drop and higher brake specific energy consumption (BSEC)were also reported in most of the cases [32]. However, there is no research report available on variation of injection timing on the combustion, performance and emission characteristics of diesel engine running with JME-TPO blends.

With this background, the present investigation is aimed to study the effect of injection timing on the combustion,performance and emission characteristics of a diesel engine fueled with JMETPO20, a typical JME-TPO blend with 80% of JME and 20% of TPO by volume.

2.MATERIALS AND METHODS

2.1 Production of Biodiesel

In the present study, the JME was prepared from raw Jatropha oil by the transesterification process. The transesterification process, also called alcoholysis is an equilibrium reaction, during which the vegetable oil reacts with alcohol to make esters of simpler molecules and glycerol in the presence of a catalyst. In this process, methanol or ethanol is typically employed as an alcohol. Methanol is the most popular alcohol in the transesterification process owing to its low price, and physical and chemical advantages. The parameters that affect the transesterification process are the reaction time, temperature, molar ratio of alcohol to oil, type of catalyst etc. The schematic diagram of this process for the production of JME is given in Fig.1.
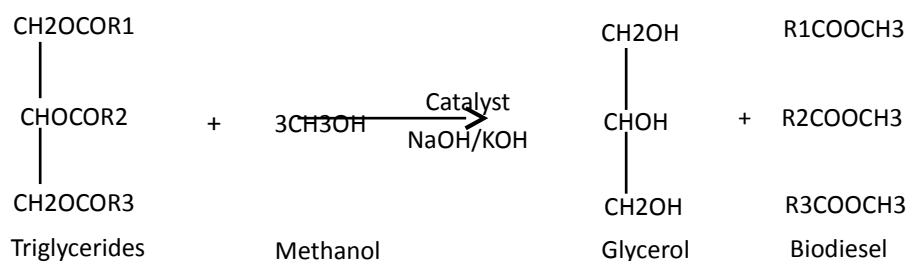
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\begin{array}{c}
CH_2OCOR_1 \\
| \\
CHOCOR_2 \\
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CH_2OCOR_3 \\
\text{Triglycerides}
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\quad + \quad
\begin{array}{c}
3CH_3OH \\
\text{Methanol}
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\xrightarrow[\text{NaOH/KOH}]{\text{Catalyst}}
\begin{array}{c}
CH_2OH \\
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CH_2OH \\
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\begin{array}{c}
R_1COOCH_3 \\
R_2COOCH_3 \\
R_3COOCH_3 \\
\text{Biodiesel}
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Fig. 1 Schematic diagram of the transesterification process

2.2 Production of Tyre Pyrolysis Oil

Pyrolysis is one of the methods to recycle the waste automobile tyres in to useful energy. Pyrolysis, the thermal fragmentationof waste tyres in theabsence of air, producesthree principal yields i.e. the pyrolysis oil, solid char and the remaining fraction as non-condensable gases like CO, CO_2, H_2, and CH_4 etc.In addition, it also yields some residualsteel product andthis entire have the potential to be recycled.In this investigation, TPO was obtained from a pilot pyrolysis plant where waste truck tyres were utilised as the feedstock.The capacity of the plant was five ton per batch. The reactor used in the pyrolysis unit was of a horizontaland rotating type. The temperature rise of the reactor was maintained between 30-40˚C/h. The highest temperature of pyrolysis was550˚C at whichmaximum yield of oil was obtained.

2.3 JMETPO20 Blend

The TPO was blended with the JME in a ratio of 20:80 by volume and the blend was kept under observation for 30 days, to ensure its stability. It was noticed that the TPO was not separated from the JME in the blend. Gas chromatography/Mass spectrometry (GC/MS) was used for analysing the composition of the JMETPO20 blend.
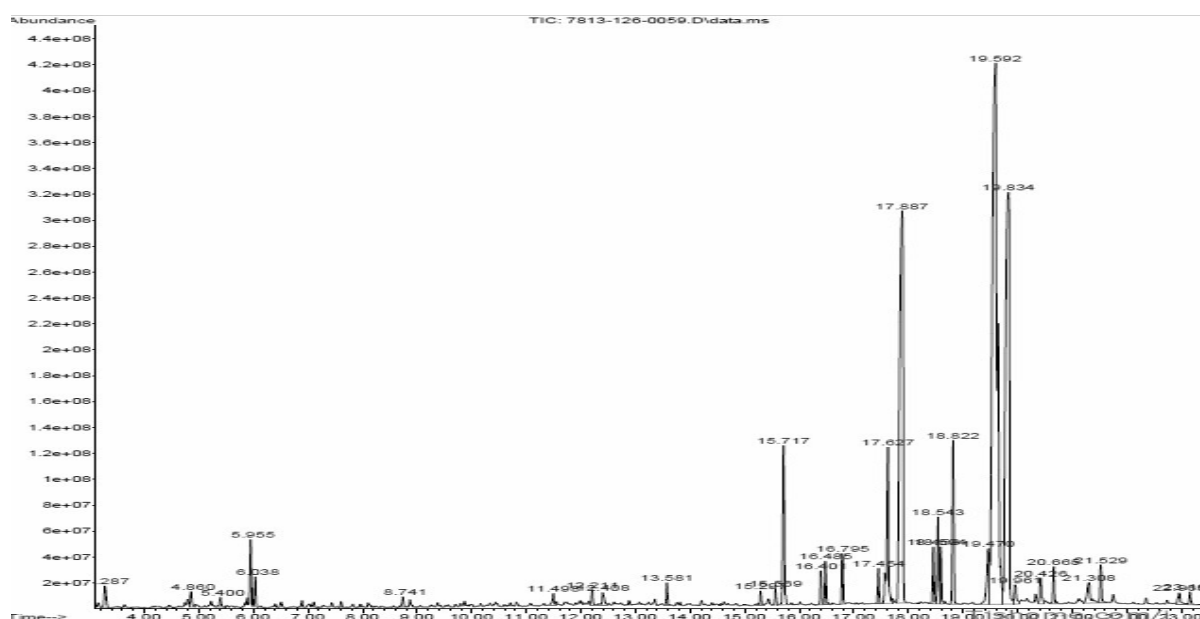

Fig. 2 GC-MS chromatogram of the JMETPO20 blend

The GC-MS indicates that the blend contains compounds like Pentadecanoic acid methyl ester, 10-Octadecenoic acid methyl ester, and Heptadecanoic acid methyl ester in large proportions as shown in Fig.2. All the functional groups show the existence of oxygen, which is due to the presence of JME in the blend. Table 1 gives the comparison of the physico-chemical properties of diesel, JME, TPO and the JMETPO20 blend.

Table 1 Physico-chemical properties of diesel, JME, TPO and the JMETPO20 blend

Properties	ASTM Test Method	Diesel	JME	TPO	JMETPO20
Specific gravity	D 4052	0.830	0.881	0.913	0.887
Viscosity (cSt)	D 445	2.6	5.6	**3.35**	5.2
LowerCalorific Value (MJ/kg)	D 4809	43.8	39.4	38.1	38.82
Flash point (˚C)	D 93	50	156	49	132
Fire point (˚C)	D 93	56	171	58	145
Carbon (%)	D 3178	86.2	77.1	86.92	79.26
Hydrogen (%)	D 3178	13.2	11.81	10.46	11.31
Nitrogen (%)	D 3179	Nil	0.119	0.65	0.23
Sulphur (%)	D 3177	0.3	0.001	0.95	0.18
Oxygen by difference (%)	E 385	Nil	10.97	1.02	9.02

3 EXPERIMENTAL

3.1EngineSetup and Measurements

The investigation wascarriedout on a single cylinder, four stroke, constant speed, air cooled, naturally aspirated, DI diesel engine, with a rated power of 4.4 kW at 1500 rpm. Fig.3 shows the schematic layout of the experimental setup, and the specifications of the test engine are provided in Table 2.The engine was coupled with an eddy current dynamometer for loading. The air consumption was measured using a sharp-edged orifice plate and U-tube manometer.A burette fitted with two optical sensors, one at a high level and, the other at a low level, was employed for measuring the quantity of fuel flow to the engine. The liquid flow through the high level optical sensor, gives a signal to the computer to start the time. Once the fuel reached the lower level optical sensor, the sensor would give a signal to the computer, to stop the time and refill the burette. The time taken for the consumption of fuel of a fixed volume was recorded. The engine exhaust gas temperature was measured using a K type (Chromel-Aluminium) thermocouple connected to a digital indicator. The Kistler type piezoelectric pressure transducer was mounted on the cylinder head for the measurement of the cylinder pressure. A TDC encoder was used to detect the engine crank angle. The engine setup was attached with a control panel, which had the capability to communicate with the pressure sensor, and to convert the signal from the pressure sensor to the analogue voltage

signal, which wasultimately fed to the data acquisition system (DAS). The exhaust gas compounds such as CO, CO_2, HC, NO, and O_2 were measured with the help of an AVL DiGas 444 exhaust gas analyser.
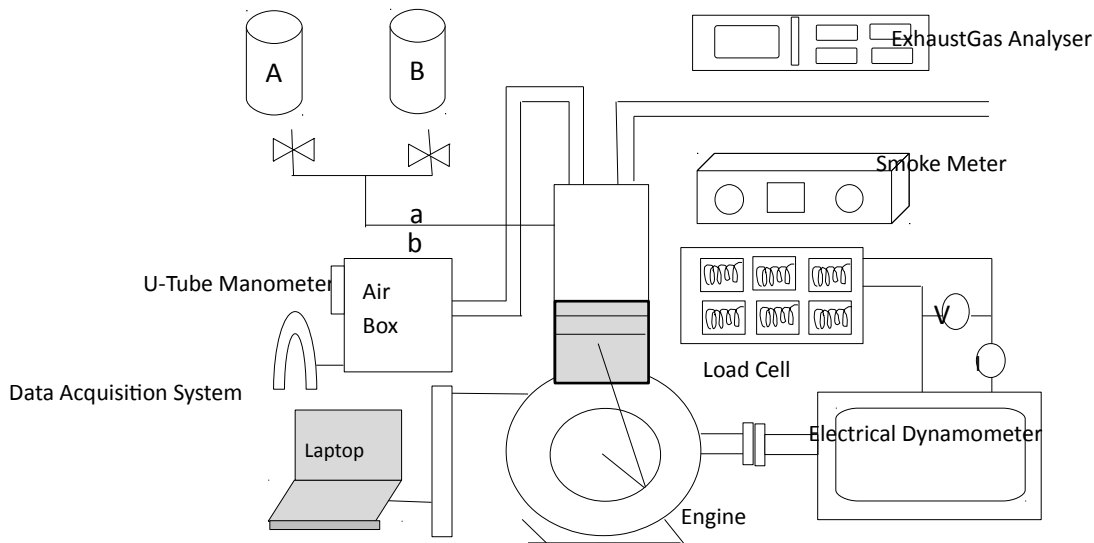

Fig. 3 Schematic layout of the experimental setup

The smoke opacity of the exhaust gas was measured by an AVL 437 diesel smoke meter. The measurements of various parameters were recorded only after the engine attained the steady state. Each test was conducted 3 times, ensuring the repeatability of the result. The values given in this study are the averages of these results. During the tests, the engine ran satisfactorily through the entire duration, and did not show any difficulty, when fueled with the JMETPO20 blend.

Initially, experiments were conducted using diesel, JME, and the JMETPO20 blend,with the original injection timing of 23˚CA bTDC (as set by the engine manufacturer) for obtaining the reference data. Further, the experiments were conducted atdifferent injection timings for the JMETPO20 blend. The original injection timing was altered by adjusting the number of shims fitted under the plunger in the pump, byaddition or removal of shims. For changing the injection timing, the number of shims was varied. Every single shim of thickness 0.25 mm shifts the injection timing by about 1.5˚CA. The experiments were carriedout using the JMETPO20 blend at five injection timings, of26, 24.5, 23, 21.5 and 20˚CA bTDC. For the original injection timing of 23 ˚CA bTDC, three shims were used in the fuel pump. The study was carried out with 1.5and 3 ˚CA advancement, and 1.5and 3 ˚CAretarding injection timing for the JMETPO20blend, and the results were compared with those of diesel, JME, and the JMETPO20blend at the original injection timing.

Table 2 Technical specifications of the test engine

Manufacturer	Kirloskar
Model	TAF 1
Engine type	Single cylinder, four stroke, constant speed, air cooled, direct injection, CI engine
Rated power (kW)	4.4
Speed (rpm)	1500 (constant)
Bore (mm)	87.5
Stroke (mm)	110
Piston type	Bowl-in-piston
Displacement volume (cm^3)	661
Compression ratio	17.5
Nozzle opening pressure (bar)	200
Start of fuel injection	23˚CA bTDC
Dynamometer	Eddy current(Make-PowerMag)
Injection type	3- Hole pump-line-nozzle injection system
Nozzle type	Multi hole
No. of holes	3
Nozzle-hole diameter (mm)	**0.25**

3.2 Instrument Accuracy and Uncertainty Analysis

The details of the measuring range, accuracy and percentage uncertainties for the instruments used in the present investigation are presented in Table 3. The overall uncertainty of the experiment was calculated by the addition of the uncertainties of the individual instruments, and is given below.

Total percentage of uncertainty of this experiment is

= Square root of { (uncertainty of total fuel consumption)^2 + (uncertainty of brake power)^2 + (uncertainty of specific fuel consumption)^2 + (uncertainty of brake thermal efficiency)^2 + (uncertainty of CO)^2 + (uncertainty of HC)^2 + (uncertainty of NO)^2 + (uncertainty of pressure transducer)^2 + (uncertainty of EGT)^2 + }

$=\sqrt{\{(1.5)^2 +(0.2)^2+(1)^2+(1)^2+(0.2)^2+(0.2)^2+(0.2)^2+(0.05)^2+ (1.0)^2+(0.15)^2\}}$ = ±2.33

Thus the total uncertainty for the whole experimentation was found to be ±2.33.

Table 3Measuring range, accuracy and percentage uncertainties of various instruments

S.No	Instruments	Measuring Range	Accuracy	Percentage Uncertainties
1	AVL DiGAS 444 five exhaust gas analyser			
	Carbon Monoxide (CO)	0-10% vol	±0.02% vol	±0.2
	Carbon dioxide (CO_2)	0-20 % vol	±0.03% vol	±0.15
	Hydrocarbon (HC)	0-20000ppm	±15 ppm	±0.2
	Oxygen (O_2)	0-22 % vol	±0.15% vol	±0.3
	Nitric Oxide (NO)	0-5000ppm	±50 ppm	±0.2
2	AVL 437 smoke meter	0-100%	±1	±1
3	Exhaust gas temperature	0-900 ºC	±1 ºC	±0.1
4	Burette for fuel	1-30cc	±0.2cc	±1
5	Pressure transducer	0-100 bar	±0.1 bar	±0.15
6	Crank angle encoder	0-720˚CA	±0.2˚CA	±0.5
7	Speed measuring unit	0-10000 rpm	±10 rpm	±0.1
8	Load cell	250-6000W	±10 W	±0.2

4. RESULTSAND DISCUSSION

The results related to the combustion, performance and emission characteristics of a DI diesel engine fueled with the JMETPO20 blend at different injection timings are compared with those of the JME and diesel operation and are presented in the subsequent section.

4.1 Combustion Parameters

4.1.1Cylinder Pressure History

The cylinder pressure variation with respect tothe crank angle data can be used to obtain quantitative information on the progress of combustion. Fig.4illustratesthe variation ofthe cylinder pressure with crank angle, for diesel, JME, and the JMETPO20 blend with different injection timingsatthe brake mean effective pressure (BMEP) of 5.6 bar. It can be observed from the figure that the variation of injection timing affects the cylinder pressure of the JMETPO20 blend remarkably.It is found that at BMEP of 5.6 barand the original injection timing, thestart of combustion occursat about348.5, 347.2 and 348.4˚CAin the case of diesel, JME and the JMETPO20 blend respectively.It is also observed that at the original injection

timing and BMEP of 5.6 bar, the combustion starts a little earlier in the case of JME, as compared to that of diesel and the JMETPO20 blend.
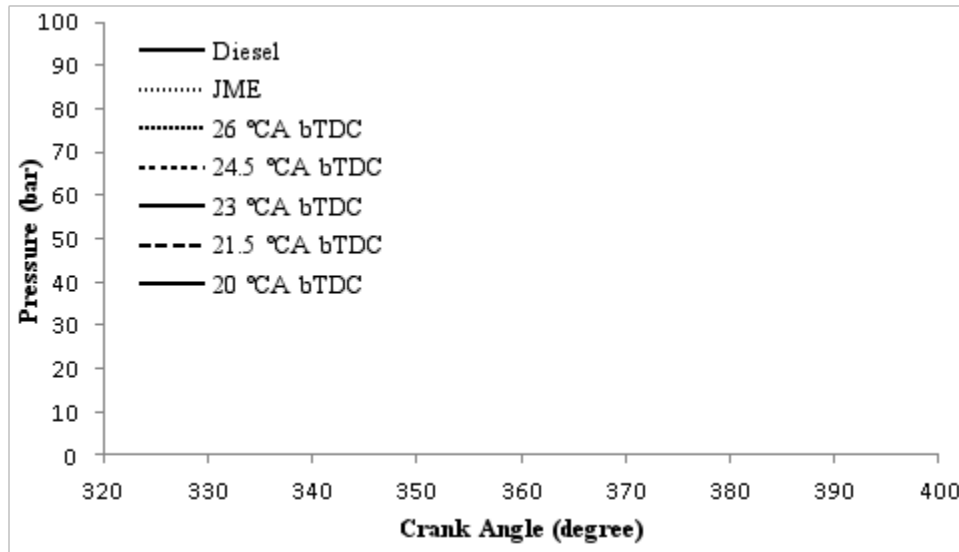

Fig.4 Variation of the cylinder pressure with crank angleat different injection timings

This is due to thehigher cetane numberand the oxygen bound combustion of JME [33]. Forthe JMETPO20 blend at an advanced injection timings of 26and 24.5°CA bTDC,the start of combustion occurs at about 348.7 and 348.3°CArespectively whilefor a retarded injection timings of 21.5and 20°CA bTDC,it occurs at 349.3 and 348.1°CA respectively at BMEP of 5.6 bar. It is evident from the figure, that the start of combustion occurs earlier for advanced injection timings, compared to that of the original and retarded injection timings at BMEP of 5.6 bar. It can also beobserved for the JMETPO20 blend, that advanced injection timings cause an increase inthe cylinder pressure as compared to the original and retarded injection timings at BMEP of 5.6 bar. This is due to a faster burning rate inthe premixed combustion phase [34]. At retarded injection timings, reduced cylinder pressures are observed, which may be due to the delayed burning of fuel, which continues after TDC in the expansion stroke. The maximum cylinder pressures for diesel, JME, and the JMETPO20 blend at the original injection timing and BMEP of 5.6 barare found to be about 80.96, 80.6 and 79.95 bar respectively.At BMEP of 5.6 barand an advanced injection timings of 26 and 24.5 °CA bTDC, the maximum cylinder pressure values are found to be about 83.7 and 82.6 bar respectively. At BMEP of 5.6 barand the retarded injection timingsof 21.5and 20 °CA bTDC, the values of the maximum cylinder pressure are recorded as 68.2 and 62.7 bar respectively.

4.1.2 Ignition Delay

The ignition delay is an important parameter in the analysis of the combustion behaviour of a CI engine and, is evaluated as the time difference measured in terms of the crank angle between the start of injection and the start of ignition [35]. Fig.5presents the variation ofthe ignition delay with the BMEP of 5.6 barfor diesel, JME, and the JMETPO20 blend at different injection timings.It is apparent from the figure that with an increase in the BMEP of 5.6 bar, the ignition delay decreases for all the test fuels in this study. This is because, as the engine load increases, the heat loss during compression decreases, resulting in higher temperature and pressure of the compressed air, and a shorter ignition delay is obtained [36]. The values of ignition delay for diesel, JME and the JMETPO20 blend at BMEP of 5.6 barand original injection timing are 11.51, 10.15, 11.36 °CA respectively.
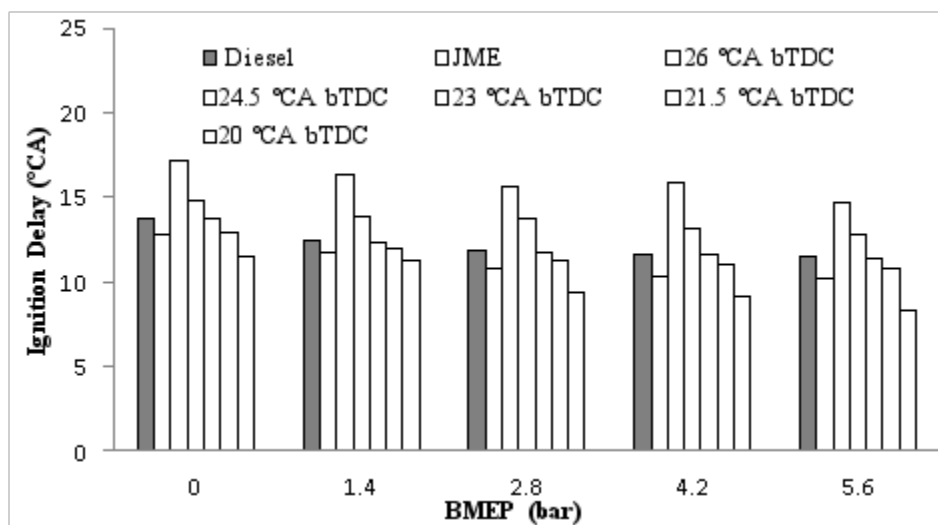
Fig.5 Variation of the ignition delay with BMEPat different injection timings

The ignition delay of diesel is found to be longer compared to those of JME, and the JMETPO20 blendat BMEP of 5.6 barand the original injection timing.The higher cetane number of JME and the JMETPO20blendmakes autoignition easy which gives a better ignition quality and results in a shorter ignition delay. With the advanced injection timings of 26and 24.5°CA bTDC, the values are found to be about 14.64 and 12.83°CArespectively, while atthe retarded injection timings of 21.5and 20°CA bTDC the values are about 10.71and 8.26°CArespectively,at BMEP of 5.6 bar. It is observed that the JMETPO20 blend exhibited a slightly longer ignition delay at BMEP of 5.6 barand advanced injection timings. This is because at the early start of fuel injection, the cylinder air temperature and pressure are going to be lower; resulting in an increase in ignition delay. Compared to original injection timing, when injection starts close to TDC, the shorter values of ignition delay arefound for the

JMETPO20 blend. This is becausethe spray experiences comparatively high temperature and pressure of air and this result in a decrease in ignition delay.

4.1.3 Heat Release Rate

The amount of heat release in the premixed combustion of a CI engine depends on the ignition delay, air fuel mixing rate, and the heating value of the fuel [37]. Fig. 6 illustrates the heat release rate (HRR) pattern with respect to the crank angle for diesel, JME, and the JMETPO20 blend at the BMEP of 5.6 barand different injection timings.The HRR is an important parameter for the analysis of the combustion phenomenon in the engine cylinder, as the combustion duration and ignition delay can be easily estimated from the heat release rate-crank angle diagram. The HRR in this study was calculatedusing the cylinder pressure data[38]. The heat release rate at each °CA was determined by the following formula, which is governed by the first law of thermodynamics.

$$\frac{dQ}{d\theta} = P\frac{\gamma}{\gamma-1}\left(\frac{dV}{d\theta}\right) + \frac{1}{\gamma-1}V\frac{dP}{d\theta} \quad \dots\dots\dots\dots\dots\dots\dots\text{Eq}^n 1$$

where$dQ/d\theta$is the rate of heat release (kJ/deg), $P$is the incylindergas pressure (bar), $V$is incylinder volume (m³), and γ is the ratio of specific heats.
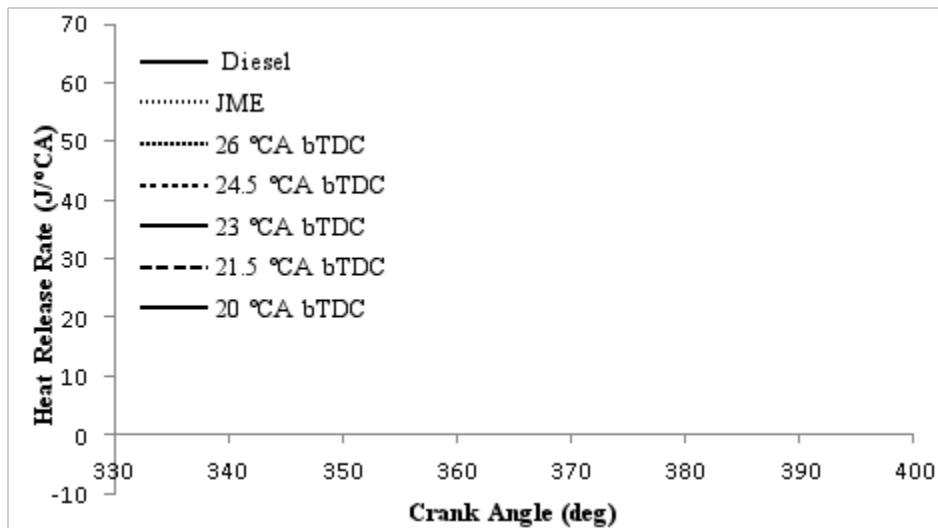

Fig. 6 Variation of the heat release rate at different injection timings

The maximum HRR is foundfor diesel, among all the three test fuels at original injection timing and BMEP of 5.6 bar. This may be due to the higher calorific value of diesel, and accumulation of more fuel owing to the longer ignition delay of diesel. At the original injection timing and BMEP of 5.6 bar, the maximum HRR for diesel, JME and,the JMETPO20 blend are found to be about 56.41, 52.43 and 50.36 J/°CA respectively.Similarly,

atBMEP of 5.6 barand advanced injection timings of 26and 24.5˚CA bTDC, the values of the maximum HRR for the JMETPO20 blend are 52.21 and 51.42J/˚CArespectively. The maximum HRR is higher at advanced injection timing for the JMETPO20 blend,and this is attributed to the accumulation of more fuel due to a longer ignition delay.This increases the amount of fuel burnt during the premixed combustion phase which also results in a higherHRR. The values of maximum HRRfor the JMETPO20 blend at BMEP of 5.6 barand retarded injection timings of 21.5and 20˚CA bTDC are found 48.09 and 43.63 J/˚CArespectively.At retarded injection timing,the maximum HRRfor the JMETPO20blend are found to be lower, because as the fuel is injected near the TDC,more amount of heat goes to the exhaust.

4.1.4 Combustion Duration

The combustion duration is described as the time required by the combustion process to reach 90% of its mass fractions burned[39]. Fig.7depicts the variation of the combustion duration for all the test fuelsat different injection timings. The combustion duration increases with an increase in the BMEP for all the test fuels in this studydue to an increase in the quantity of fuel injected. It is also evident from the figure, that at the original injection timing and BMEP of 5.6 barthe combustion duration is found to be shorter for the JME and theJMETPO20blend, compared to that of diesel. This isdue tothe high cetane number and the oxygen content of JME which helped the complete combustion. The values of the combustion duration for diesel, JME, and the JMETPO20blend are found to be about 38.4, 37.9 and 43.34˚CA respectively, at BMEP of 5.6 barand the original injection timing.
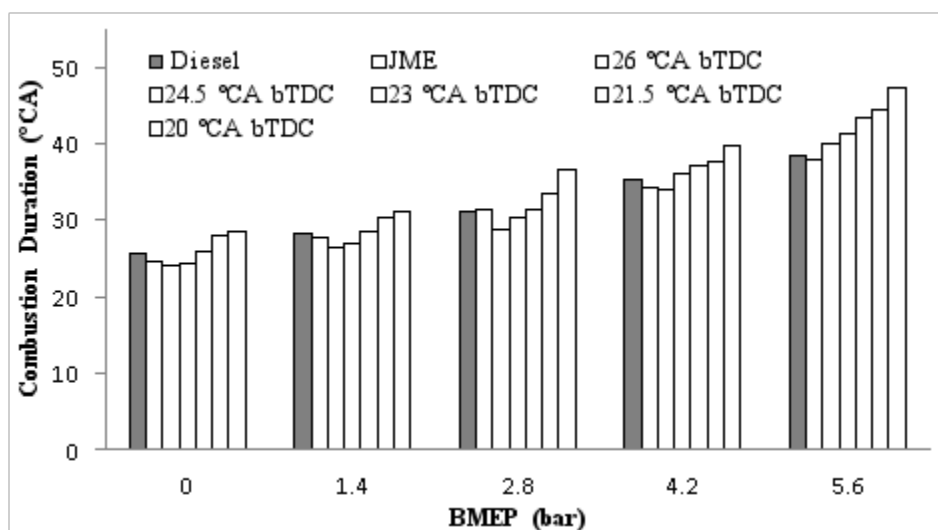

Fig. 7 Variation of the combustion duration with BMEPat different injection timings

With the advanced injection timings, the combustion duration is found to be reduced, while at retarded injection timings, it is found to be increased for the JMETPO20 blend. This is due to the longer ignition delay at advanced injection timing which results infaster burning rate of the fuel and rapid rise of thepressure and temperature inside the cylinder. Therefore, most of the air-fuel mixture burns in premixed phase and causes maximum HRR and shorter combustion duration. At retarded injection timing, comparatively less air-fuel mixture is accumulated resultingin shorter ignition delay. It leads to slowerburning rate and gradual rise in pressure and temperature inside the cylinder. Therefore, relatively moreair-fuel mixture burns in diffusion phase than in premixed phaseleading to lower maximum HRRand longer combustion duration[40]. The values of the combustion durationare found to be about 40.1, 41.3, 44.35and 47.37°CA, with an injection timing of 26, 24.5, 21.5and 20°CA bTDC respectively,at BMEP of 5.6 bar.

4.1.5 Maximum Rate of Pressure Rise

The rate of pressure rise of an engine refers to the smoothness of the engine operation.Ideally, the rate of pressure rise should not exceed 5 bar/°CA in a single cylinder, four stroke, DI diesel engine [41]. Thevariations of the maximum rate of pressure rise with BMEP for diesel, JME, and the JMETPO20 blend at different injection timings, are shown in Fig.8.The maximum rate of pressure rise at the original injection timing for diesel varies from 2.63 to 5.25 bar/°CA and for the JMETPO20 blend it varies from 2.74 to 5.02 bar/°CAwith respect toBMEP.The rate of pressure rise is found to be higher with advanced injection timings because of faster combustion.
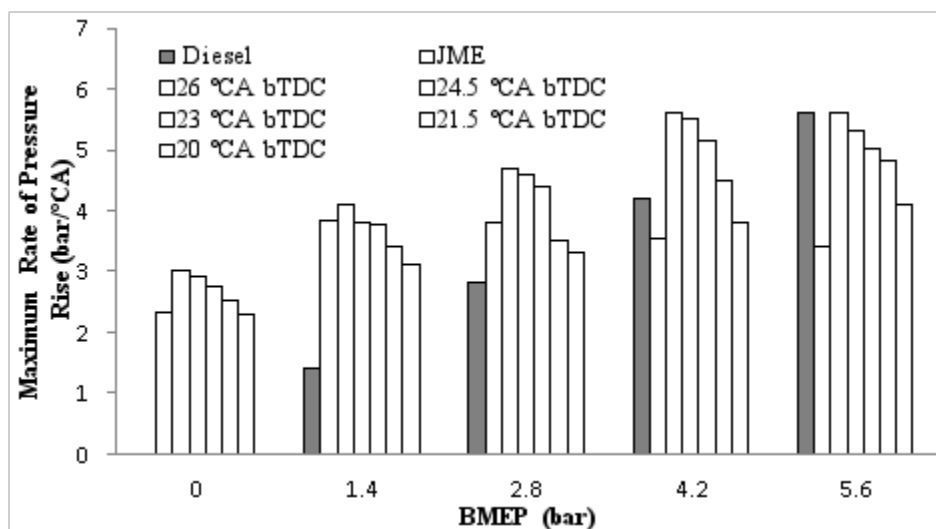
Fig. 8 Variation of the maximum rate of pressure rise with BMEPat different injection timings

The values of maximum rate of pressure rise at BMEP of 5.6 barand injection timings of 26, 24.5, 21.5, 20°CA bTDC are found to be 5.6, 5.3, 4.8 and 4.1bar/°CArespectivelyfor the JMETPO20blend. It can be observed from the figure that at advanced injection timings,maximum rate of pressure rise increases for the JMETPO20 blend. The reason is that the cylinder air pressure and temperature at the point of injection fall, resulting in more fuel beingburnt during uncontrolled combustion phase because of longer ignition delay and, finally this leads to, an increased maximum rate of pressure rise [42].

4.2Performance Parameters

4.2.1 Brake Specific Energy Consumption

The brake specific fuel consumption (BSFC) is not a reliable factor when two fuels of different calorific values and densitiesare blended together [43]. The BSEC is described as the multiplication of the BSFC and lower calorific value of the fuel. Fig.9 illustrates the variation of the BSEC for diesel, JME, and the JMETPO20 blend with the BMEP at different injection timings. As shown in the figure, the BSEC for the JME is found to be higher compared to that of diesel, because of the lower energy content of JME. At the original injection timing and BMEP of 5.6 bar, the values of BSEC for diesel, JME, and the JMETPO20 blend are recorded as 11.86, 12.79 and 12.55 MJ/kWh respectively.
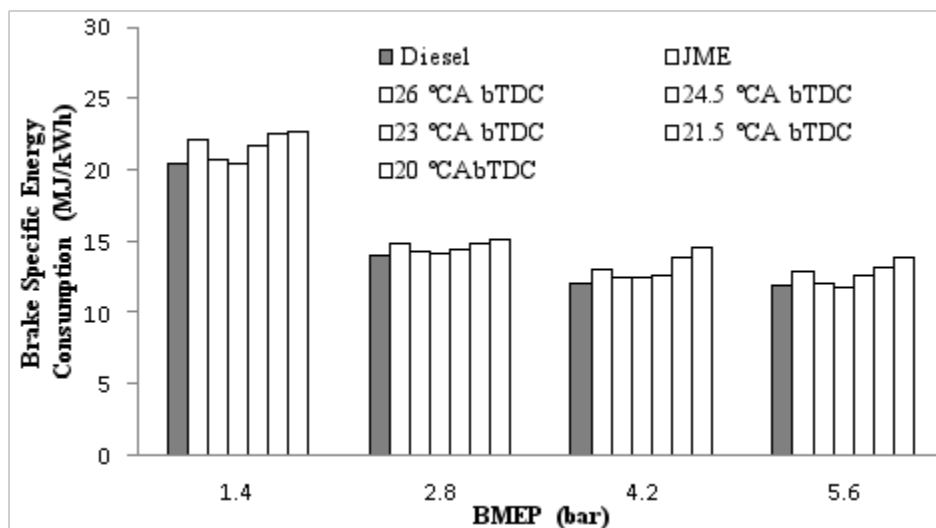

Fig. 9 Variation of theBSEC with BMEPat different injection timings

In the case of the JMETPO20 blend, when the injection timing is advanced by 1.5 and 3 °CA bTDC, the BSEC decreased by about 7.1% and 4.14% compared to that of the original injection timing at BMEP of 5.6 bar.But with the retarded injection timing of 1.5 and 3 °CA bTDC, the BSEC increased by about 4.63% and 10.3% respectively as compared to that of the original injection timing at BMEP of 5.6 bar.Retarding the injection timing means delayed combustion, which causes a loss of power and, hence,a higher BSEC is noticed. The lowest value of BSEC for the JMETPO20 blend is found to be about 11.66 MJ/kWh, at BMEP of 5.6 bar and an advanced injection timing of 24.5°CA bTDC.

4.2.2Exhaust Gas Temperature

The exhaust gas temperature (EGT) provides qualitative information about the progress of combustion in the engine [44]. The variational trend for the EGT with diesel, JME, and the JMETPO20 blendat different injection timings is graphically depicted in Fig.10.The EGT increases with an increase in the BMEP of 5.6 bar, as a result of increased cylinder gas temperature. It is evident from the figure that the EGT increases, when the injection timing is retardedas compared to that of the original injection timing of JMETPO20 blendat BMEP of 5.6 bar.This is because, with the delayed combustion, more amount of heat goes to the exhaust. At the original injection timing, the values of EGT are recorded to be about 303, 333 and 335 °C for diesel, JME, and the JMETPO20 blend respectively, at BMEP of 5.6 bar.
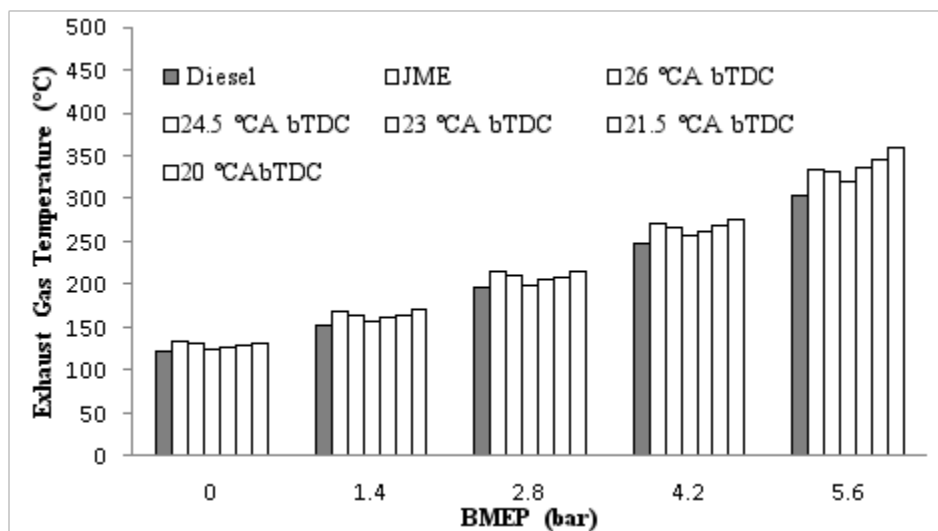

Fig. 10 Variation of the exhaust gas temperaturewith BMEPat different injection timings

For the JMETPO20 blend at the advanced injection timing of 26and 24.5°CA bTDC, the values of EGT are found to be 330 and 320°C respectively, andat the retarded injection timing of 21.5and 20°CA bTDC, the values of EGT are recorded as 344 and 358°C respectively, at

BMEP of 5.6 bar.It can be observed from figurefor the JMETPO20 blend that the EGT decreased as injection timing was advanced from 23 to 24.5 °CA bTDCat BMEP of 5.6 bar. The EGT reduced by about 4.5% when injection timing was advanced by 1.5 °CA bTDC at BMEP of 5.6 bar. This may be attributed to the fact thatat advanced injection timing, wall heat transfer is more owing to earlier start of combustion.This leads to the lowering of the exhaust gas temperature.

4.3 Emission Parameters

4.3.1 Carbon Monoxide Emission

During a C.I. engine operation, the parameters which affect the CO formation are the equivalence ratio, fuel type, combustion chamber geometry, atomization rate, injection timing, injection pressure, engine load and speed [45].
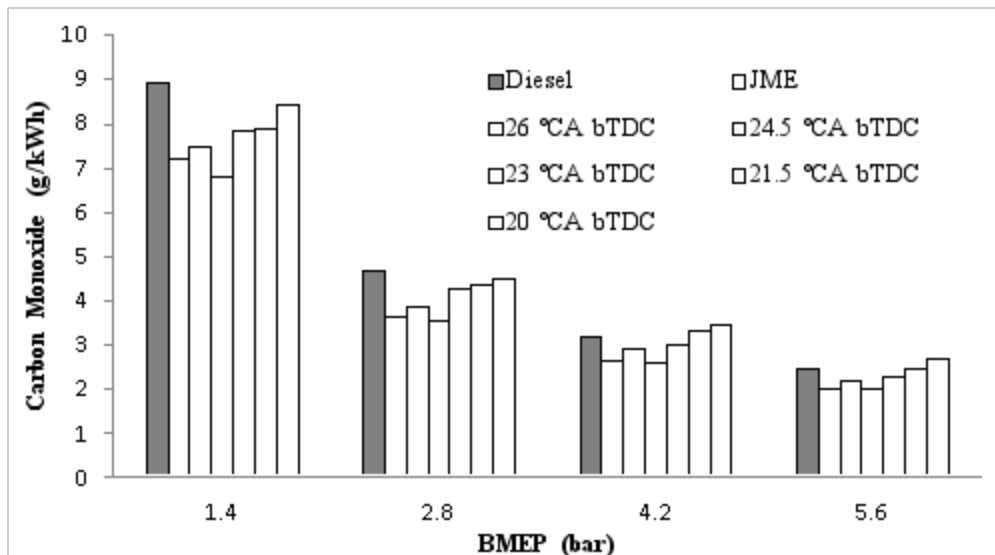

Fig. 11 Variation of thecarbon monoxideemission with BMEPat different injection timings

Normally, the CO emission from a CI engine is negligible, becausethe engine operates with excess air. But in the present investigation, since a new blend is experimented, the CO emissions at different injection timings are recorded. Figure 11 presents a comparative picture of the CO emission for various test fuels with BMEP at different injection timings.The test results reveal thatfor the JMETPO20blend with the advanced injection timings of 26and 24.5 °CA bTDC, the CO emission is found to be lower compared to that withthe original injection timing by about 4.76% and 13.26% respectively, at BMEP of 5.6 bar.This is due to the fact that more time is being available for the complete combustion in case of advanced injection timings. Contrary to this, the CO emission is found to be increased by about 7.1% and 16.8%

with the retarded injection timing of 21.5and 20˚CA bTDC respectively, compared withthat atthe original injection timing and full load.This is because of late burning of the fuel injected, and incomplete combustion. Further, relatively lower value of the CO emission is recorded for the JMETPO20 blend atBMEP of 5.6 barand advanced injection timing of 24.5˚CA bTDC, which is lower by about 19.3% and 1% than that of diesel and JME at BMEP of 5.6 bar.

4.3.2 Hydrocarbon Emission

Figure 12presents the change in the HC emission from the engine, using diesel, JME, and the JMETPO20 blendat different injection timings. The HC emissions for the JME and JMETPO20blend at all injection timings are found to be lower compared to that for diesel at full load. It can also be noted that with the advanced injection timing, the HC emission decreases.
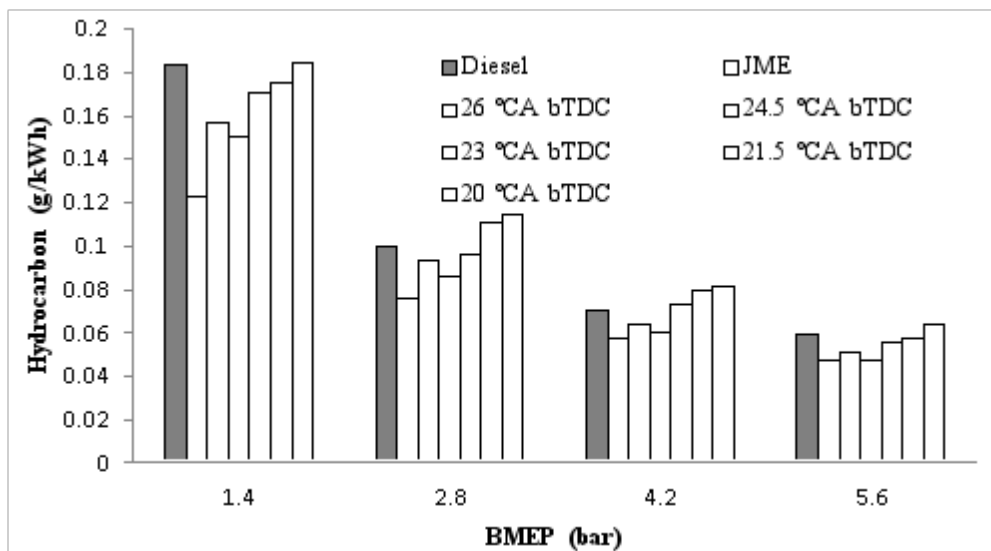

Fig. 12 Variation of theunburnt hydrocarbon emission with BMEPat different injection timings

This is because of the earlier start of combustion comparative to TDC, which helps inthe complete combustion as the fuel-air mixturegets compressed with the piston moving to the TDC, resulting in a relatively higher temperature [46]. It can also be observed that when the injection timing is retarded, the HC emissions are found to be more as compared to those with original and advanced injection timings.It is evident from the figure, the advanced injection timings of 26and 24.5˚CA bTDC cause a reduction in the HC emission by about 7.53% and 14.2%, respectively and the retarded injection timing of 21.5and 20˚CAbTDC

raise the HC emission by about 4.1% and 14.6%,respectively compared to that of the original injection timing of 23°CA bTDC for the JMETPO20blend, at BMEP of 5.6 bar.

4.3.3Nitric Oxide Emission

It has been known that theNOformation in a CI engine is predominantly influenced by the maximum combustion temperature,residence time and the oxygen concentration[47]. The effects of the injection timings on the NO emission for diesel, JME, and the JMETPO20blendare compared in Fig.13. The NO emission increases with the increase in the engine load,due to the rise in combustion temperature.With the increase in engine load, more fuel needs to be burned, which results in arise in combustion temperature and subsequently a greateramount of NOemission.[48].The results show that, when the injection timing is advanced, the NO emission for the JMETPO20 blend increases significantly under all engine loads, due to a higher combustion temperature caused by better fuel-air mixture burning.
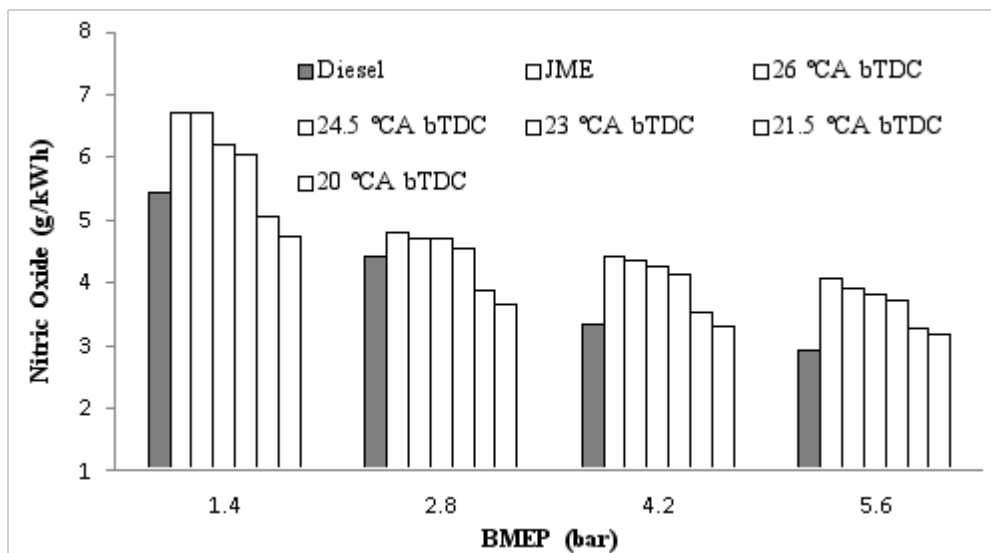

Fig. 13 Variation of thenitric oxideemission with BMEPat different injection timings

The NO emission for the JMETPO20blend at an advanced injection timing 26and 24.5°CA bTDC ishigher by about 4.9% and 2.1% than that of the original injection timing at BMEP of 5.6 bar. With the retarded injection timing of 21.5 and 20°CA bTDC,the JMETPO20 blend produces a lower NO emission by about 12% and 14.9%, compared to that of the original injection timing at BMEP of 5.6 bar. The NO emission decreases at retarded injection timing compared to original and advanced injection timings. This is due to the fact that at retarded injection timing, fuel is injected near the TDC and most of the fuel burn after TDC. It causes

higheramount of heat going to the exhaust which results in lowering of maximum cylinder pressure and temperature.

4.3.4Particulate Emission

The variation of the particulate emissionwith BMEPfor diesel, JME, and the JMETPO20 blendat different injection timings is depicted in Fig 14. At the original injection timing and BMEP of 5.6 bar, the particulate emissionis found to be about 86.3%, 52.2% and 63.1% for diesel, JME, and the JMETPO20 blend respectively. The particulate emissionfor the JMETPO20 blend is lower by 9.3% at an advanced injection timing of 24.5°CAbTDC, compared to that of original injection timing. This is due to the availability of more time for the oxidation process between carbon and oxygen molecules which results better combustion process by the early start of fuel injection[49]. It is also found that at retarded injection timing results in a higherparticulate emission, which is attributed to the increased fraction of diffusion combustion.
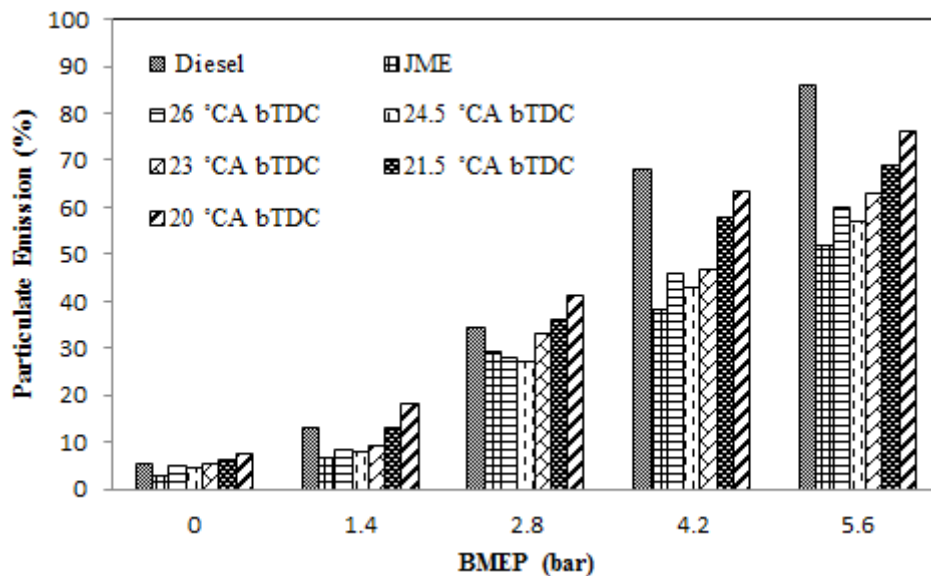

Fig. 14Variation of theparticulate emissionwith BMEPat different injection timings

At BMEP of 5.6 bar, the values of particulate emissionfor the JMETPO20 blend are about 60.2%, 57.2%, 69.3% and 76.5%atthe injection timings of 26,24.5, 21.5 and 20°CA bTDC, respectively.

5. CONCLUSIONS

Fuel injection timing is undoubtedly an important parameter that influences the combustion, performance and emission characteristics of any diesel engine. In this study, the influence of the injection timing on these characteristics of a single cylinder, four stroke, air cooled,

naturally aspirated, DI diesel engine were experimentally investigated, when the engine was run with the JMETPO20 blend, at five different injection timings (26, 24.5, 23, 21.5 and 20˚CA bTDC). Based on the experimental results obtained for the JMETPO20 blend, the following specific conclusions are drawn:

- Advancedinjection timing results in increase in maximum cylinder pressure and heat release rate, while the reverse trend is noticed in case of retarded injection timing.At an advanced injection timing of 24.5 ˚CAbTDC the maximum cylinder pressure was found to increase by about 2.73bar, compared to that withthe original injection timing at BMEP of 5.6 bar.Similarly, the ignition delay was found to be longer with shorter combustion duration at an advanced injection timing of 24.5˚CAbTDC,compared to that withthe original and retarded injection timings.The maximum heat release rate at theadvanced injection timing of 24.5 ˚CAbTDC was found to be 51.42 J/˚CA, whichis 1.1 J/˚CAhigherin comparison with that the original injection timing.

- At the advanced injection timing, BSEC decreased as early start of fuel injection ensures more complete combustionowing to improved reaction between fuel and oxygen. The BSEC at an advanced injection timing of 24.5 ˚CA bTDCis lower by about 7.1% thanthat withthe original injection timing at BMEP of 5.6 bar.

- The experimental investigation revealed that, advancing the injection timing results in reduced the CO, HC and particulate emission. On the other hand the NO emission increased.The CO and HC emission were lower by about 14.2% and 13.26% at theadvanced injection timing of 24.5 ˚CA bTDC and BMEP of 5.6 bar,compared to that withthe original injection timing.Similarly, the NO emission was higher by about 2.1% at the advanced injection timing of 24.5 ˚CA bTDC,in comparison to that withthe original injection timing. The particulate emissionwas found to be lesser by about 9.3% at the advanced injection timing of 24.5 ˚CA bTDC compared to that withthe original injection timing.

On the whole, it is concluded that the advanced injection timing of 24.5˚CA bTDC was theoptimum injection timing, which givessignificant superior results in terms of the combustion, performance and emission characteristics of the engine fueled with the JMETPO20 blend.The findings of the study suggest that JMETPO20 blend has adequate potential to be an alternative engine fuel in future. It is also Worthing that the discarding of scrap tyres from automobiles is an increasing environmental problem. Pyrolysis of waste tyres is one of the possible solutions of their recycling

and reutilization leading to reduced environmental impact and petroleum dependence.In future, this study can be extended to multi cylinder diesel engine and similar experiments can be conducted to optimaze other engine operating parameters for better results.

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