Improvisation of Combustion Behaviour of Jojoba Oil Diesel Blend Fuelled DI Diesel Engine by Engine Modifications Such as MOP and TBC

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ABSTRACT: *To reduce the importance of fossil fuels, the identification of biofuels plays a vital role. The plant oil chosen for this study is novel plant oil named Jojoba oil (the botanical name is Simmondsia Chinensis). To utilize this type of oil in higher proportion to diesel, engine modifications were carried out. The engine modifications include optimizing salient operating parameters with Thermal Barrier Coating (TBC). Taguchi and Grey relational methods were used for finding the optimized values of salient operating parameters like injection pressure, compression ratio, injection timing, and intake air temperature as 275 bar, 19.5 CR, 27.5 bTDC, and 65˚C, respectively [1]. This has helped to combust the higher blends of jojoba oil, namely 60J, 70J, and 80J, without adverse performance and emission characteristics. The fundamental aim of coating Aluminium oxide, Molybdenum, and Titanium oxide (40%, 30%, and 30%) on the inner surface of the piston crown and the cylinder head is to retain heat and thereby achieve higher thermal efficiency. Combustion, performance, and emission analysis were done and found that 60% by volume of jojoba oil can be applied in a TBC engine which offers 11.5% higher BTE, 74.3% lower CO, 31.2% lower HC, 8.6% higher NOx and 25.9% lower smoke than 70% and 80% by volume of jojoba oil.*

KEYWORDS: *Jojoba oil; Combustion; Thermal barrier coating; Emission; Performance.*

INTRODUCTION

The role of the thermal barrier coating is to reduce the heat loss to the coolant by enhancing the heat resistance in the heat flow from the combustion chamber to the coolant. TBC engine is more suitable for Bio-diesels, and it also increases the temperature of working gases and exhaust gases [2].

Rapid development in the world economy due to large-scale industrial development and globalization lead to the exploration of new energy sources to cater to the steady increase in energy needs [3]. Since the industrial revolution, wood, coal, electricity, petroleum products, solar energy, windmill, fuel cell, hydrogen as a fuel

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are significant sources of energy depending upon the availability in a particular country [4]. Among the above, all petroleum products as an energy source have unanimously dominated the world irrespective of geographical boundaries.

A world without fossil fuels is unimaginable; all activities will come to a sudden halt due to our current lifestyle, which directly or indirectly depends on fossil fuels [5]. To overcome the above problems and search for a substitute, Vegetable oils are one of the most desirable sources of alternate fuel due to their renewable, no sulphur content, less emission, and lubricity [6]. Moreover, the steady, sharp increase in demand throughout the world increases the purchase price of crude oil, and any political, and social problems within or between oil supply countries result in a steep rise in crude oil price and even non-availability of crude oil [7]. This resulted in a considerable loss in foreign exchange for the majority of non-oil-bearing countries. Moreover, the manifold increase in usage of the automobile throughout the world has led to severe environmental threats due to pollution caused by greenhouse gases in engine exhaust [8]. These lead to the exploration of alternative energy sources available locally and renewable. First among them is biofuel oil derived from locally available plant seeds, saving foreign exchange and improving the local economy and new job opportunities for local people worldwide.

Many researchers have found that the use of vegetable oils in engines is designed for petroleum fuels, which will lead to severe engine damage in the long run [9]. Since vegetable oils have adverse properties like larger molecular size, high viscosity, low volatility, and high surface tension take a longer time to combust than fossil fuels [10–14]. This can be overcome entirely by designing an engine specifically for vegetable oil which can have a longer combustion duration. This is practically not feasible because lack of infrastructure to supply biofuel to automobiles, which will be very costly [15]. This can be made possible by inventing internal combustion engines with thermal barrier coating ranging from small to extensive applications and almost in all fields.

Jojoba seeds are collected from jojoba plant botanical name is Simmondsia Chinensis it is a shrub that grows to a height of up to 5 meters, and the life span of jojoba plant is up to 200 years. Seeds of Jojoba fruit contain 44-56% oil monounsaturated esters or wax in dark brown seeds, mainly three seeds in each fruit [16]. Oil is extracted by mechanical first and second pressing, followed by leaching by anyone of the solvents hexane, toluene, benzene, petroleum ether, or isopropanol [17]. To aid the highest proportion of Jojoba oil combustion in the engine, more heat is retained inside the cylinder by coating Aluminium oxide, Molybdenum, and Titanium oxide on the inner surface of the piston crown and the cylinder. The main aim of this work is to replace the maximum possible amount of fossil fuel with plant oil and reduce major pollutants without compromising fuel efficiency.

EXPERIMENTAL SECTION

The experimental setup details are shown in Fig. 1. In this research, Kirloskar TAF1 four-stroke, single-cylinder, air-cooled direct injection diesel engine constant speed 1500 rpm developing 4.4 kW was used. Table 1 gives the detailed Specification of the engine. An eddy current dynamometer varies the output power of the engine with a control system coupled to it. Cylinder pressure and crank angle data are obtained by software named ‘Engine soft’, a Lab view-based software. Heat release rate, mass fraction burnt, rate of pressure rise, and other performance parameters are also obtained by using the same software. Anti-pulsating drum, air temperature indicator air preheater, and gas admission manifold are attached to the intake side of the engine. A combustion analyzer, temperature indicator, smoke sampler, and gas analyses are fitted to the exhaust side of the engine. Burette and stopwatch were used to measure fuel consumption and an anti-pulsating drum for measuring air consumption. The air preheater heat-up intake air and air temperature are measured by temperature indicator. Smoke opacity, pollutant concentrations, and exhaust gas temperature are measured by the smoke sampler, exhaust gas analyzer, and temperature indicator, respectively, and are fitted to the exhaust side of the engine.

RESULTS AND DISCUSSION

The combustion, performance, and emission analysis of higher blends of jojoba oil were tested and presented in the following sections.

Combustion Analysis

Cylinder Pressure

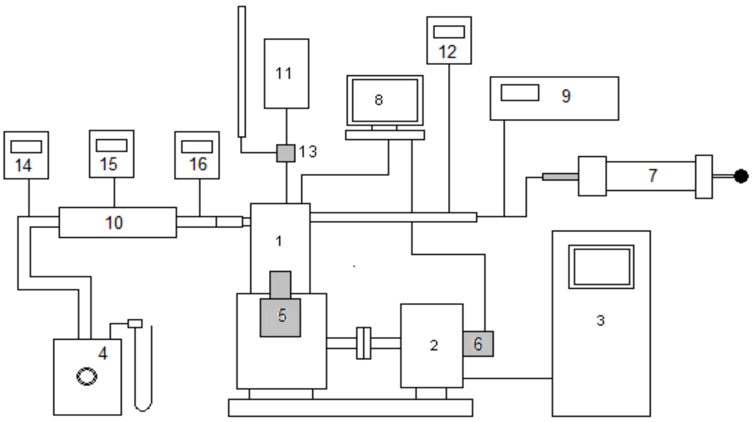
Fig. 2 shows the variation in-cylinder pressure with a crank angle for various proportions of jojoba-diesel blends.

Table 1: Engine specifications.

Make and Model	Kirloskar TAF1, Four-stroke, compression ignition, constant speed, air-cooled, direct injection
Number of cylinders	One
Bore	87.5 mm
Stroke	110 mm
Cubic capacity	661 cc
Compression ratio	17.5:1
Rated speed	1500 rpm
Rated output	4.4kW
Fuel injection timing	23º bTDC
Injector opening pressure	180 bar

Table 2: Physical & Chemical Properties of Diesel and Jojoba oil.

Properties	Jojoba oil	Diesel
Molecular Weight (average)	606	200
Density kg/m^3@20ºC	905	820
Specific Gravity @20ºC	0.91	0.82
Boiling PointºC	398	180-340
Viscosity cSt @ 20ºC	22	4-5
Latent Heat of Vaporization kJ/kg	-	230
Lower Heating Value kJ/kg	38,100	42,700
Flash Point º C	225	74
Fire point (°C)	338	81
Auto Ignition Temperature ºC	<250	250
Flammability limit % Volume	1.0 – 5.2	1.0 – 6.0
Moisture content (%water)	< 0.05	-
Iodine value (g/100 g)	82	-
Saponification value	92	-
Cetane Number	45-48	45-50



1- Diesel Engine, 2- Eddy current Dynamometer, 3- Dynamometer Control, 4- Anti-pulsating Drum, 5- Fuel Injection Pump, 6- Crank angle encoder, 7- Smoke sampler, 8- Computer with DAQ, 9- Gas Analyser, 10- Air-preheater, 11- Diesel tank, 12- EGT indicator, 13- Two-way valve, 14- Air inlet temperature indicator, 15- Energy meter, 16- Air temperature indicators

Fig. 1: Schematic layout of the Experimental setup.

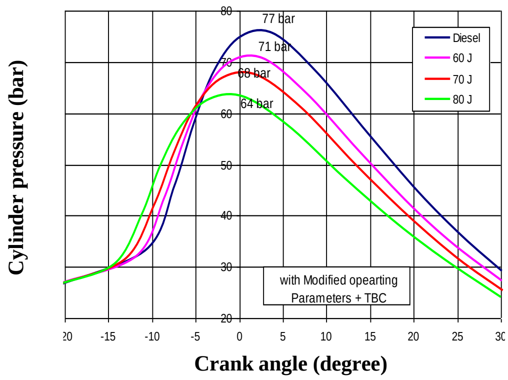


Fig. 2: Variation of cylinder pressure with a crank angle for various proportions of jojoba-diesel blends at full load using.

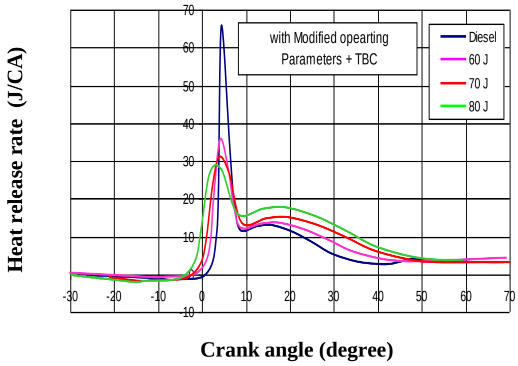


Fig. 3: Variation of HRR with the crank angle for various proportions of jojoba-diesel blends at full load

From the figure, it is seen that the increasing jojoba content decreases cylinder pressure. In other words, a higher jojoba blend offers lower cylinder pressure, and a lower jojoba blend offers higher cylinder pressure. This is due to the low combustion behavior caused by the adverse fuel properties of neat jojoba oil in the blend [18]. However, various modifications provided in the engine overcome these issues and improve the performance and emission characteristics. All the modifications used in this method collectively improve the combustion behavior by increasing the heat content of the combustion chamber. More specifically, the modified operating parameters improve spray characteristics and increase adiabatic heat. The Thermal Barrier Coating (TBC) retains more heat inside the combustion chamber and increases the rate of mixture preparation.

The hot combustion chamber caused by the TBC helps to crack down the heavier molecular structure at a rapid rate and produces HC fractionates. These HC fractionates, in turn, help to combust better and produces higher cylinder pressure

The figure shows that 60J produces 71 bar peak pressure at full load, which is 3.5 bar and 7 bar higher than 7J and 8J and 6 bar lower than diesel fuel, respectively. This shows that the modifications have changed the combustion performance of all jojoba blends in a better way. However, the changes depend on the quantity of jojoba oil in the blend. Higher jojoba blends offer shorter premixed phases and longer duration of combustion. This effect causes a lower heat release rate and a lower rate of pressure rise [19]. Therefore, the higher jojoba blends such as 70J and 80J offer lower cylinder pressure than 6J. It is also seen that the SOI of the blends advances with increasing jojoba proportion. Hence, 8J starts combustion at 14 degrees bTDC, which is 2, 4, and 6 degrees earlier than 60J, 70J, and diesel fuel, respectively.

Heat Release Rate

Fig. 3 shows the variation of Heat Release Rate (HRR) with the crank angle for various proportions of jojoba-diesel blends. The figure shows that the rate of net heat release decreases with increasing jojoba content. The higher jojoba blend offers an early start of combustion and a longer duration of combustion than the lower jojoba blend. Usually, neat oil starts combustion earlier than diesel fuel due to the rapid production of intermediate compounds or HC fractionates. This behavior was seen in all jojoba blends as they have a considerable fraction of jojoba oil in them.

All jojoba blends offer both faces of combustion with varying rates of HRRs. The higher jojoba blend offers a lower rate of heat release at the first and second phases of combustion. It also offers a longer duration of combustion than the lower jojoba blend. However, the rate of heat release and the duration of combustion changes concerning the quantity of jojoba oil in the blend [20]. The duration of combustion is also one of the essential parameters to determine the performance and emission characteristics of the engine. From the figure, it is also found that the jojoba content determines the duration of combustion. That is, the higher jojoba blend burns longer than, the lower jojoba blend. This is attributed to the heavier molecular structure, higher viscosity, and poor volatility of the neat jojoba oil present in the blend [21].

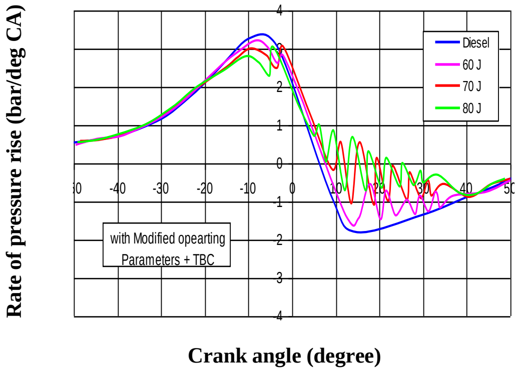


***Fig. 4:** Variation of RPR with the crank angle for various proportions of jojoba-diesel blends at full load.*

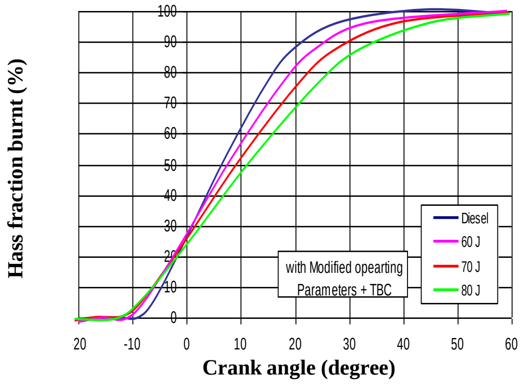


***Fig. 5:** Variation of MFB with the crank angle for various proportions of jojoba-diesel blends at full load.*

The figure shows that 80J starts combustion at 5 degrees bTDC, which is 2, 4, and 6 degrees earlier than 60J, 70J, and diesel fuel. Similarly, the burn duration of 80J extends up to 48 degrees, which is 10, 7, and 4 degrees longer than diesel, 60J, and 70J. The engine modifications such as MOP and TBC have helped to combust higher jojoba blends.

Rate of Pressure Rise

Fig. 4 shows the Rate of Pressure Rise (RPR) variation with the crank angle for various proportions of jojoba-diesel blends. From the figure, it is seen that the RPR decreases with increasing jojoba content. That is, higher jojoba blends offer lower RPR, and lower jojoba blends offer higher RPR. The figure also shows that the higher jojoba blend offers more pressure fluctuation at the tail end of combustion. This could be caused by the secondary combustion of neat oil in the blend [22].

The collective effect of MOP & TBC increases the heat content of air which helps to crack down the heavier molecules of jojoba oil. However, a minor difference has been observed between the blends as they had a variable fraction of jojoba content. However, its performance and emission characteristics were not adversely affected due to engine modifications. Therefore, 80J offers the lowest RPR among the used blends, and its duration extends 12, 8, and 5 degrees longer than diesel, 60J, and 70J, respectively**.**

Mass Fraction Burnt

The Mass Fraction Burnt (MFB) is also an essential combustion parameter, which helps to know how effectively the fuel burns inside the cylinder. This parameter also helps to predict the emission characteristics of the fuel. Fig. 5 shows the variation of MFB with the crank angle for various proportions of jojoba-diesel blends. The figure shows that the fuel blend that has a higher proportion of Jojoba extends the duration of MFB. This was mainly due to the heavy molecular structure and low volatility of jojoba oil in the blend [23].

The adverse fuel properties are not the only reason for the poor combustion behavior of the jojoba blend. The production of HC fractionates and their combustion was also the reason for the imperfect combustion nature of jojoba oil. More specifically, the production of HC fractionates consumes a considerable amount of heat from the combustion chamber while breaking down its double bonds. In addition to it, the lighter fractions also reduce the combustion behavior as they have a lesser number of carbons and behave like low-cetane fuels [22]. These are the primary reasons for the poor combustion behavior of jojoba blends. However, this tendency changes concerning the jojoba proportion of the blend.

The engine modifications used in this method help to increase the combustion temperature and reduce the adverse effects of neat oil combustion. More specifically, TBC helps to retain more heat inside the combustion chamber and improves spray parameters.

The MFB of fuel has a direct relationship with the rate of heat release and the rate of pressure rise. Therefore, higher jojoba blends offer a lower heat release rate and a lower rate of pressure rise. This is the main reason for the lower cylinder pressure and lower BTE [24]. This parameter also influences the emission characteristics,

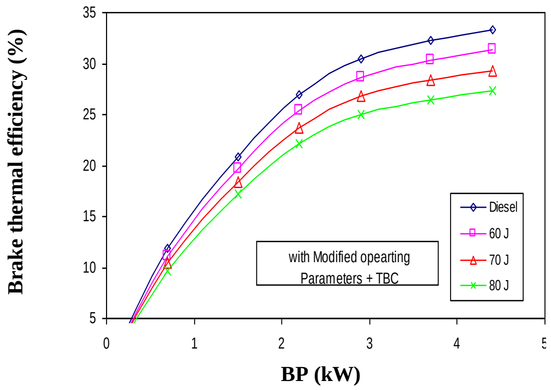


Fig. 6: Variation of BTE with BP for various proportions of jojoba-diesel blends.

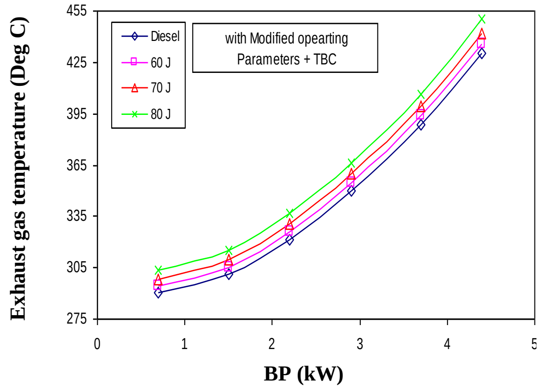


Fig. 7: Variation of EGT with BP for various proportions of jojoba-diesel blends.

and hence the higher jojoba blends liberate higher emissions than the lower jojoba blends. The figure shows that 80J offers 90% MFB at 35 degrees after the TDC, which is 10 degrees longer than 60J and 14 degrees longer than diesel fuel operation. Similarly, 60% MFB of 80J is 5 degrees longer than 60J and 7 degrees longer than diesel fuel operation.

Performance analysis

Brake Thermal Efficiency

Fig. 6 shows Brake Thermal Efficiency (BTE) variation with brake power for various proportions of jojoba-diesel blends. The figure shows that higher jojoba blends offer lower BTE and lower jojoba blends offer higher BTE. This was mainly due to the low combustion characteristics caused by the unsuitable fuel properties such as higher viscosity, heavier molecular structure, and low volatility of neat jojoba oil present in the blend. Usually, neat oils emit more HC, CO, and smoke compared to other fuels. Also, it poses lube oil dilution and injector clogging during long-term operation. Hence, it cannot be mixed with more than 20% volume of diesel oil. However, the suitable engine modifications used this method permits the neat oil to more than 20% by volume.

Higher viscosity, heavier molecular structure, and poor volatility of neat jojoba oil present in the blend prevent a higher proportion of neat oil blends. Higher combustion temperature resulted in increased efficiency for lower blends than higher blends. 60J blends produce 4% and 6% higher efficiency compared to 70J and 80J, respectively.

Exhaust Gas Temperature

Fig. 7 shows Exhaust Gas Temperature (EGT) variation with brake power for various proportions of jojoba-diesel blends. The figure shows that the EGT of the blend increases with the increasing proportion of Jojoba. The higher jojoba blend offers higher EGT, and the lower jojoba blend offers lower EGT. This was mainly due to the poor combustion characteristics of unmodified jojoba oil in the blend [25].

The EGT directly relates to the duration of combustion, i.e. the fuel that has a longer duration of combustion offers higher EGT. It indicates the poor MFB and poor rate of heat release. It also shows the poor rate of pressure rise and lower cylinder pressure [26]. This parameter is also used to predict the emission characteristic of the fuel, i.e. the fuel that releases higher EGT emits higher HC and CO.

The present work uses the engine modifications such as MOP and TBC to provide high-temperature combustion. This has helped to combust the neat oil without adverse loss of performance and emission characteristics. The fuel properties such as higher viscosity, poor volatility, and heavier molecular structure were also considered prime sources for the higher EGT. Poor oxygen availability, sluggish combustion, and rapid production of HC fractionate was another reason for the higher EGT [27].

In addition to it, the combustion of HC fractionates consumes a higher amount of oxygen and develops an oxygen scarcity in the middle of the combustion. This was the main reason for the onset of sluggish combustion in the jojoba blends. However, this had been removed by suitable engine modifications. Hence, the higher jojoba blends

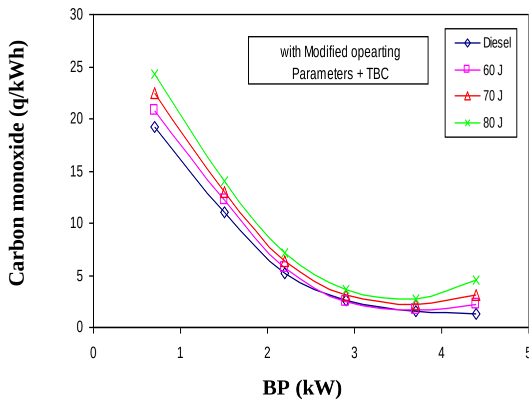


Fig. 8: Variation of CO emission with BP for various proportions of jojoba-diesel blends.

such as 60J, 70J, and 80J have performed well in the present method without adverse loss of performance and emission characteristics. From the observed results, it is seen that 80J offers 450°C EGT at full load, and it is 20, 14, and 8 higher than diesel, 60, and 70J, respectively

Emission analysis

Carbon monoxide Emission

Fig. 8 shows the variation of Carbon Monoxide (CO) emission with brake power for various proportions of jojoba-diesel blends. The figure shows that CO emission increases with the increasing proportion of jojoba content, i.e. higher jojoba blend offers higher CO emission than the lower jojoba blends. This was mainly due to the poor combustion characteristics caused by the undesirable fuel properties of neat jojoba oil in the blend [28]. More specifically, the poor volatility, heavier molecular structure, and longer combustion duration are the prime reasons for the higher CO emission.

The CO emission is a product of partial combustion, and it is produced due to insufficient oxygen content. This was caused by the excessive consumption of oxygen by the combustion of HC fractionate. The Fractionates are the breakdown products of FAs. It is produced at the time of the beginning of combustion. It is shorter in carbon chain length, and hence it combusts faster than long-chain fractionates. However, engine modifications such as MOP and TBC help improve combustion behavior by offering higher combustion temperatures. The higher combustion temperature is the only key to suppressing all the issues about neat oil combustion. More specifically, the higher combustion temperature helps to break down the heavier molecular structure in a short duration of time. This improves the rate of mixture preparation, rate of pressure rise, and heat release rate [29]. As a result, combustion emits lesser CO for all the blends of jojoba diesel.

The figure also shows that the CO emission decreases when BP increases. This is mainly due to the increase in combustion temperature with increasing load. When the load increases, the quantity of fuel also increases, and thus the combustion temperature increases. This is the main reason for the lowering of CO emission with increasing load. However, this behavior changes concerning the jojoba proportion of the blend. From the observed results, it is found that 80J offers 4.5 g/kWh CO at full load, and it is 71%, 51% and 31% higher than diesel 60and 70J, respectively

Hydrocarbon Emission

Hydrocarbon (HC) emission is an indirect indicator of combustion quality. It also indicates the effective utilization of the fuel by the engine. Fig. 9 shows the variation of Hydrocarbon (HC) emission with brake power for various proportions of jojoba-diesel blends. From the figure, it is seen that HC emission increases with the increasing proportion of Jojoba. That is, a higher jojoba blend emits higher HC than a lower jojoba blend. It is also seen that the HC emission decreases with increasing load.

HC emission is governed by many factors, such as fuel properties and combustion ambiance. More specifically, the fuel properties such as heavier molecular structure, poor volatility, higher viscosity, and unsaturated molecular structure contribute more to HC production. The heavier molecular structure reduces the rate of mixture preparation and lengthens the combustion duration [30]. Heavier molecular fuels take a longer time to disintegrate their molecular structure and hence produce fuel vapor even after the completion of the expansion stroke. This is the main reason for the higher HC emission of higher jojoba blends. This trend augments when the jojoba content of the blend increases, and hence, higher jojoba blends emit more HC than lower jojoba blends.

The poor combustion ambiance caused by insufficient oxygen is also attributed to the higher HC emission. This is mainly due to the combustion of HC fractionates. The HC fractionates consume a large amount of oxygen at the time of combustion [31]. This creates an oxygen scarcity in the middle of the combustion. Hence, the fuel vapor

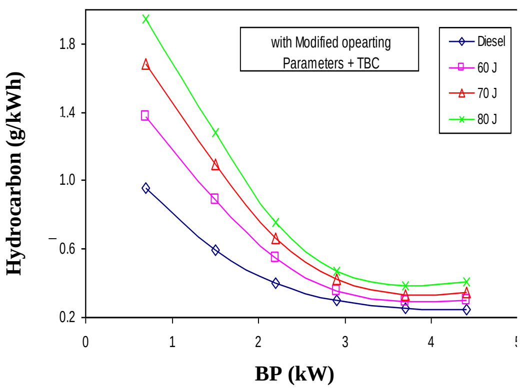


Fig. 9: Variation of HC emission with BP for various proportions of jojoba-diesel blends.

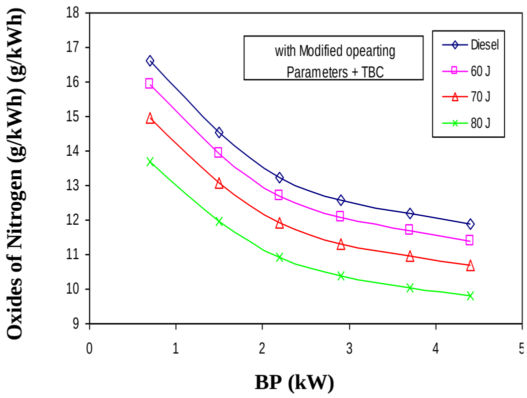


Fig. 10: Variation of NOx emission with BP for various proportions of jojoba-diesel blends.

that participates at the tail end of combustion finds insufficient oxygen and fails to burn. These vapors will be taken away by the exhaust gas as HC emissions. The figure shows that 80J offers 0.4 g/kWh HC emission at full load, 39%, 26%, and 17% higher than diesel, 60J, and 70J, respectively. From the figure, it is also seen that the HC emission decreases with increasing load. When the load increases, the quantity of fuel also increases, and thus, the combustion temperature increases. This is the main reason for the decrease in HC emission with increasing load.

Oxides of Nitrogen Emission

Fig. 10 shows the variation of Oxides of nitrogen (NOx) emission with brake power for various proportions of jojoba-diesel blends. From the figure, it is found that NOx emission decreases with an increasing fraction of jojoba content, i.e. higher jojoba blends emit lower NOx than the lower jojoba blends.

There are two different mechanisms, such as Thermal NOx and Prompt NOx, used to explain the production of NOx from combustion. Thermal NOx is temperature dependent, whereas the Prompt NOx depends on the quantity of HC fractionates in the combustion [32]. It was proved that the higher jojoba blends offer a lower rate of heat release and lower combustion temperature. Hence, the fuel blend that carries a higher fraction of Jojoba emits less NOx than the blend that carries lower Jojoba. Therefore, the blend 80J emits 9.8 g/kWh NOx, which is 21%, 16%, and 9% lower than diesel, 60J, and 70J, respectively.

Smoke Opacity

Smoke opacity is an indirect indicator of combustion effectiveness and the suitability of the fuel. Fig. 11 shows the variation of smoke opacity with brake power for various proportions of jojoba-diesel blends. From the figure, it is observed that 80J offers the highest smoke number among the used blends. However, the smoke number of all jojoba blends is higher than diesel fuel. This is mainly due to unsuitable fuel properties such as higher viscosity, poor volatility, and heavier molecular structure of neat jojoba oil present in the blend [33]. Higher viscosity affects the spray characteristics and reduces air entrainment. The poor volatility extends the duration of evaporation and reduces the combustion temperature. These are the other few reasons for the smoky exhaust of the jojoba blends. The combustion behavior of unmodified plant oils is not like diesel fuel because its molecular structure is different from that of diesel fuel. It has much unsaturation in its molecular structure, and hence it produces HC fractionates after the injection. These fractionate consume a major fraction of oxygen and deplete oxygen availability in the middle of the combustion [34]. As a result, a smoky exhaust had been produced from the jojoba blends. However, the smoke intensity differs concerning the jojoba content of the blend, i.e., a higher jojoba blend offers higher smoke emissions than a lower jojoba blend. From the observed results, it is found that 80J offers 55 % Smoke opacity at full load, which is 34%, 22%, and 14.5% higher than diesel, 60J, and 70J, respectively.

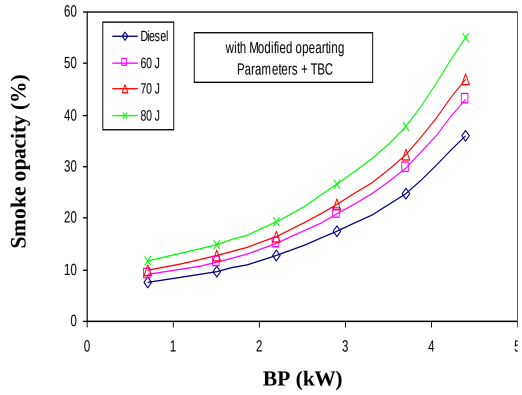


Fig. 11: Variation of Smoke Opacity with BP for various proportions of jojoba-diesel blends.

CONCLUSIONS

The effect of TBC on neat oil combustion is explained by comparing the combustion, performance, and emission characteristics of various blends with diesel. The above investigation found that blends of more than 70J had failed to perform well in the combined MOP & TBC mode. It indicates that blends more than 70J need more hot combustion, which cannot be offered by any of the modifications available at present.

i. However, the changes depend on the quantity of jojoba oil in the blend. Higher jojoba blends offer shorter premixed phases and longer duration of combustion. This effect causes a lower rate of heat release and a lower rate of pressure rise. Therefore, the higher jojoba blends such as 70J and 80J offer lower cylinder pressure than 60J.

ii. Higher combustion temperature resulted in increased efficiency for lower blends than higher blends. 60J blends produce 4% and 6% higher efficiency compared to 70J and 80J, respectively.

iii. Many unsaturations in higher blends consume a major fraction of oxygen, depleting oxygen availability in the middle of the combustion, and increase smoke emissions. However, 60J blend produced lower smoke among the blends.

From the above three investigations, it was found that the neat Jojoba can be applied up to 60% by volume in the CI engine. The blends of more than 60% are not appropriate to operate a CI engine as they were offering inferior performance and emission characteristics.

Nomenclature

Al_2O_3	Aluminium oxide
BDC	Bottom Dead Center
BP.	Brake Power
BTE	Brake Thermal Efficiency
CO_2	Carbon dioxide
CO	Carbon monoxide
CI	Compression Ignition
CR	Compression Ratio
DICI	Direct Injection Compression Ignition Engine
EGT	Exhaust gas temperature
HRR	Heat Release Rate
HC	Hydrocarbon
Mo	Molybdenum
Ni Cr	Nickel Chromium Alloy
NO_x	Oxides of Nitrogen
TBC	Thermal Barrier Coating
TiO_2	Titanium oxide

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