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EFFECT OF PINE OIL –PONGAMIA METHYL ESTER BLENDS IN A DI DIESEL ENGINE

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ABSTRACT

A double biofuel strategy to completely eliminate the use of diesel in a diesel engine without any engine modification. The conventional petroleum fuels for internal combustion engines will be available for few years only, due to tremendous increase in the vehicular population. Moreover, these fuels cause serious environmental problems by emitting harmful gases into the atmosphere at higher rates. Generally, pollutants released by engines are CO, Unburnt hydrocarbons, NOx, smoke and limited amount of particulate matter.

Pine oil, synthesized from pine oleoresin, is recently being viewed as a potential renewable source of fuel for diesel engine application. Significantly, the estimated physical and thermal properties of pine oil are suited for its use in diesel engine, with the notable advantages of lower viscosity, boiling point and comparable calorific value with diesel. In this study, we decidedly conceived a strategy to blend it with a biodiesel, instead of diesel, so as to look out for double biofuel, a measure aimed at complete replacement of fossil fuels. As such, in the current investigation, POME (Pongamia methyl ester), a biodiesel derived from Pongamia oil, was blended with pine oil in various proportions such as B25P75, B50P50 and B75P25. Further, the major emissions such as HC (hydrocarbon), CO (carbon monoxide) and smoke forB50P50 were observed to be 8.1%, 18.9% and 12.5% lower than diesel at full load condition, while NOX (oxides of nitrogen) emission was in par with diesel.
Keywords: Concept of double biofuel, less viscous pine oil and high viscous POME, Characteristics for B50P50 were in par with diesel.

INTRODUCTION

The Energy comes in a variety of renewable forms like wood energy, wind energy, solar energy, ocean water power, geothermal energy. Bio energy generated by bio fuels is viewed as a strong source of energy in the coming years. The Energy is also available in the nonrenewable form of fossil fuels that is oil, natural gas and coal, which provide almost 80% of the world's supply of primary energy. Use of these fossil fuels is a major source to cause pollution of land, sea and the entire atmosphere. India is the world's largest importer edible oil followed by European Union and China. India is the world's thirdlargest consumer after China and the EU. A growing population, increasing rate of consumption and increasing per capita income are accelerating the demand for edible oil in India.

The demand for energy, excessive reliance on crude oil importand growing environmental devastation has fostered the researchand development on alternate renewable source of fuels, known asbiofuels. Most often, these biofuels are derived from biological rawmaterials and could be classified into two categories based on theirviscosity, viz less and high viscous fuels. While vegetable oil and itsderivatives, biodiesel, could be regarded as high viscous fuels, alcohols and ethers can be termed as less viscous fuels. Alcohol basedfuels such as ethanol and methanol, are more amenable for its usein spark ignition engine, while the use of biodiesel and other etherbased fuels are becoming more prominent in compression ignitionengine. However, in the past decade, researchers have contemplated on using alcohol based fuels in diesel engine too, due to demand for petroleum diesel and the fact that alcohols are alsocompatible for its use in diesel engine. Though the use of purealcohols in diesel engine is unfeasible, considering the insurmountable challenges with their poor ignition properties and lower calorific value, they can find their use in diesel engine by modifyingthe engine design, particularly the fuel injection system.

However, they can be used as blend fuels such as alcohol–diesel blendand alcohol–diesel emulsion in a diesel engine without any modifications, which is regarded as the simplest and attractive method,though complete replacement of diesel in any case is impossible.Research studies on the use of other less viscous fuel, in thelikes of alcohols, such as eucalyptus oil and pine oil have also garnered much attention in the recent times; as the fuel properties of them are conducive for their operation in diesel engine.Similar to alcohols, these fuels have lower viscosity; however, unlike alcohols, they have comparable caloric value with diesel. Notably, eucalyptus oil, which falls under the category of essential oilderived from plants, has been proven to be a potential substitutefor diesel in the recent past Typically, both these fuels were used inblends with diesel and are reported to have shown better performance, combustion and emission characteristics.Over the past few years, investigation on the use of less viscousfuels such as ethanol, methanol and eucalyptus oil with biodiesel, instead of diesel, have also been reckoned. In this regard, Anand et al., as a measure to completely eliminate the use of diesel,studied the combustion, performance and emission characteristicsof a diesel engine fueled by a blend of 90% karanja methyl ester and10% methanol. The study reported an increase in maximum thermal efficiency by 4.2% at 80% load, with the simultaneous reduction in NOX (oxides of nitrogen) and smoke emission. Soon afterthe realization of improved performance with alcohol–biodieselblends, Yilmaz and Sanchez compared the performance andemission characteristics of a diesel engine fueled by biodiesel–ethanol and biodiesel–methanol blends, and the outcome of theirwork implied that biodiesel–ethanol blends are more effectivethan biodiesel–methanol blends in respect of engine performanceand emission.

To help enhance the combustion characteristicsand exclude the use of conventional diesel as fuel, Kasiramanet al.]Demonstrated the use of less viscous camphor oil withCSNO (cashew nut shell oil), a high viscous vegetable oil, in variousproportions (10–30%) and showed better engine characteristics. Ina recent study, Devan and Mahalakshmiblended methyl esterof paradise oil with eucalyptus oil and used them as alternaterenewable fuel for diesel engine, eluding the use of diesel completely, and reported better performance and emission than diesel.Deeper scrutiny of all available literatures shows some endeavors, in the recent past, to use less viscous fuels in blends with eitherdiesel or biodiesel. Further, it has been reliably construed that lower alcohols such as methanol and ethanol could be blended witheither diesel or biodiesel only in lower proportions due to its lowerheating value and higher latent heat of vaporization. Nonetheless, the other contemporary less viscous bio derived fuel, eucalyptus oil, could be added in higher percentages with diesel/biodiesel, as it is reported to have comparable calorific value withdiesel. Distinctly, the blending of eucalyptus oil kind of fuelswith biodiesel would give a priority of complete replacement ofdiesel, without compromising on the engine performance andemission.

Despite the immense benefits of blending fuels having lowerviscosity and better calorific value with biodiesel, little consideration has been shed to develop blends of such kind, known as double biofuels, and investigate them in a diesel engine. To fulfill thislimitation, in the current study, pine oil biofuel, endowed withlower viscosity and comparable calorific value with diesel, hasbeen chosen to be blended with high viscous biodiesel, POME (pongamiamethyl ester). The benefits of double biofuel, which is to completely replace diesel, has been reaped thoroughly and distinctly, blending of pine oil with biodiesel has not been investigated sofar. As such, pine oil was blended with POME in various proportionssuch as B25P75 (pine oil – 75% and POME – 25%), B50P50 (pine oil –50% and POME – 50%) and B75P25 (pine oil – 25% and POME – 75%), by stirring them in an ultrasonic agitator so as to keep the integrity of the blend intact. Finally, pine oil–POME blends were tested in a single cylinder diesel engine without any modification and the performance, combustion and emission characteristics of the enginewere analyzed and compared.

Pine Oil and Pongamia Oil – Overview: Currently, this study has used two feedstock viz pine oil and pongamia oil, both come under the category of biofuel, but the originof the former is from the resins of pine tree while the latter is fromthe seeds of pungai tree. Both the feedstocks, by virtue of their nature, are indigenous in their own way and do have all the probability to qualify as an alternate fuel for diesel engine. Pineoleoresin, the raw material for pine oil synthesis, is tapped frompine tree and is subjected to steam distillation, before being treated with acids to synthesize the required pine oil. Typically, pineoil, by its appearance and nature, can be regarded as one of the lessviscous fuels in the likes of eucalyptus oil, ethanol and methanol.Chemically speaking, pine oil, an alicyclic hydrocarbon, consistsof mainly cyclic terpene alcohols, known as terpineol ($C_{10}H_{18}O$)along with alpha-pinene ($C_{10}H_{16}$). Further, from its molecularstructure, it is evident that it possesses inherent oxygen, with lower molecular weight and shorter carbon chain length than diesel orbiodiesel. Notably, pine oil, despite being a higher alcohol, does notproduce any cooling effect like methanol and ethanol as the latentheat of vaporization of it is not higher like lower alcohols. On the other hand, pongamia oil, the other feedstock chosen in this study, isextracted from karanja seeds by steam treatment process followedby mechanical crushing and the extracted oil is subjected totrans-esterification process to synthesize the required biodiesel, POME.

Production of biodiesel using Esterification as follows. The methyl ester is produced by chemically reacting karanja oil with an alcohol (methyl), in the presence of catalyst. A two stage process is used for the trans esterification of karanja oil. The first stage (acid catalyzed) of the process is to reduce the free fatty acids (FFA) content in karanja oil by Esterification with methanol (99% pure) and acid catalyst sulfuric acid (98% pure) in one hour time at 57^oC in a closed reactor vessel. The karanja crude oil is first heated to 50^oC and 0.5% (by wt) sulfuric acid is to be added to oil then methyl alcohol about 13% (by wt) added. Methyl alcohol is added in excessamount to speed up the reaction. This reaction is proceeding with stirring at 700 rpm and temperature was controlled at $55\text{-}57^oC$ for 90 min with regular analysis of FFA every after 25-30 min. When the FFA is reduced up to 1%, the reaction is topped. The major obstacle to acid catalyzed Esterification for FFA is the water formation.

The production of biodiesel using trans--esterification as follows. The catalyst used is typically sodium hydroxide (NaOH) with 1% of total quantity of oil mass. It is dissolved in the 13% of distilled methanol (CH_3OH) using a standard agitator at 700 rpm speed for 20 minutes. The alcohol - catalyst solution was prepared freshly in order to maintain the catalytic activity and prevent the moisture absorbance. After completion it is slowly charged into preheated esterified oil. When the methoxide was added to oil, the system was closed to prevent the loss of alcohol as well as to prevent themoisture. The temperature of reaction mix was maintained at 60 to 65^{o}C (that is near to the boiling point of methyl alcohol) to speed up the reaction.

The recommended reaction time is 70 min. The stirring speed is maintained at 560 - 700rpm. Excess alcohol is normallyused to ensure total conversion of the fat or oil to its esters. The reaction mixture was taken each after 20 min. for analysis of FFA. After the confirmation of completion of methyl ester formation, the heating was stopped and the products were cooled and transferred to separating funnel. Once the reaction is complete, it is allowed for settling for 8-10 hours in separating funnel. At this stage two major products obtained that are glycerin and biodiesel. Each has a substantial amount of the excess methanol that was used in the reaction. The glycerin phase is much denserthan biodiesel phase and is settled down while biodiesel floated up. The two can be gravity separated with glycerin simply drawn off the bottom of the settling vessel. Once the glycerin and biodiesel phases were been separated, the excess alcohol in each phase was removed by distillation. Once separated from the glycerin and alcohol removal, the crude biodiesel was purified by washing gently with warm water to remove residual catalyst or soaps.

Test engine and instrumentation: The experimental engine used in the current study is the onethat has been typically used in agricultural applications or inindustries or generating electricity, formally known as generatoror stationary diesel engine.

DETAILS	SPECIFICATION
Make	Kirloskar-TV1
BHP& speed	5.2HP& 1500 rpm
Type of engine	single cylinder, 4 stroke, Diesel engine (Computerized)
Compression ratio	17.5:1
Bore& stroke	87.5mm & 110mm
Method of loading	Eddy current dynamometer
Load indicator	Digital, Range 0-50 Kg, Supply 230VAC
Load sensor	Load cell, type strain gauge, range 0-50 Kg
Method of cooling	Water
Orifice diameter	20mm
Type of ignition	Compression ignition
Inlet valve opening	4.5^{o}before TDC
Inlet valve closing	35.55^{o}after TDC
Exhaust valve opening	35.55^{o}before BDC
Exhaust valve closing	4.5^{o}after TDC
Injection timing	23^{o}before TDC

This single cylinder diesel engine which is a Kriloskar make, is manufactured and targeted for research studies, and the specifications of it are shown in Table. From the specifications, it could be construed that the engine hasbeen preset to run at a constant speed of 1500 rpm and for the current experimental study with pine oil–POME blends, the engineoperating conditions were maintained constant at an injectionpressure of 220 bar and injection timing of 23CA (crank angle)BTDC (before top dead center). Notably, mechanical type pump–nozzle fuel injection system was used, with the injector nozzlehaving 3 holes. In the design aspects, a piston with hemisphericalcombustion chamber has been used and the compression ratio ofthe test engine was held at 17.5.

The engine is loaded by eddy current dynamometer and the force exerted on it is measured thorough strain gauge type load cell. The fuel flow rate wasmeasured on volume basis using a burette and stop watch. Accordingly, the time taken for the consumption of 10 cc of fuel was notedand with this, the total fuel consumption was calculated. Further, the air flow rate was measured by monitoring the pressure in theU-tube manometer, attached to the orifice meter in the intake airsupply system.The in-cylinder pressure and cyclic variations of it were recorded using AVL combustion analyzer, AVL 619 Indi meter hardware and Indwin software version 2.2. The analyzer intrinsicallyhas an analog to digital converter with 16 channels, a chargeamplifier and PC interface. To measure the in-cylinder pressure, AVL piezo-electric transducer with an accuracy of 16:11 pC/barwas installed over the top of the cylinder head. The charge outputof the piezo electric transducer, quantified as desired in-cylinderpressure, was amplified using the charge amplifier and was thenconverted into digital signal using an analog to digital converter.The pressure and crank angle signals, captured and averaged after100 cycles of operation, were processed in a PC interface to obtainthe relevant combustion parameters.In the current study, emissions such as HC (hydrocarbon), CO(carbon monoxide), CO2(carbon dioxide) and NOXwere measuredousing AVL 444 di-gas analyzer on dry basis, as shown in Fig. Theexhaust sample to be evaluated was passed through a cold trap (moisture separator) and filter element to prevent water vaporand particulates from entering into the analyzer. HC and NOXemission were measured in ppm (parts per million) hexane equivalents, and CO, CO2and O2emission were measured in terms of percentage volume. These emissions are measured using the emission analyzer based on NDIR (non-dispersive infrared) principle byselective absorption. Further, the smoke level was measured inHSU (hartridge smoke unit) using a standard AVL437C smoke meter, before which, the exhaust gases were sent into a chamber withnon-reflective surfaces and were stabilized. The smoke emission ismeasured based on light extinction principle wherein, the amount of light blocked by the sample of exhaust gas from the diesel engine is measured in terms of opacity. To measure the temperatureof the exhaust gases, a K-type thermocouple was configured in theexhaust pipe and a digital temperature indicator reads the EGT (exhaust gas temperature).

Experimental procedure:

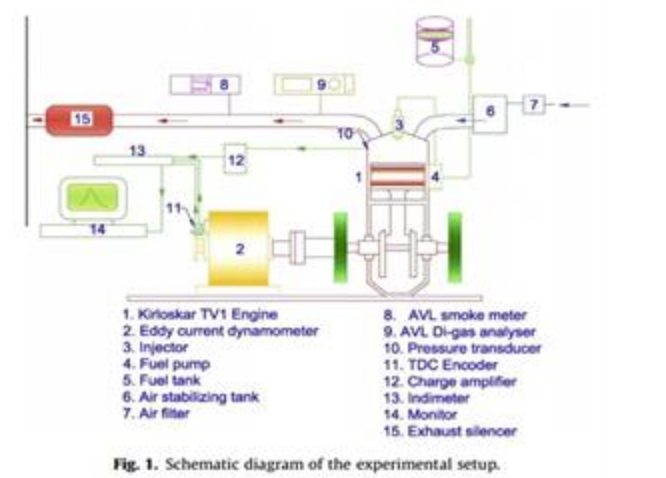

Fig.1. Schematic diagram of the experimental setup

Prior to starting the experiment with various pine oil–POMEblends, the engine was made to run with diesel for 30 min so asto attain normal working temperature environment. After the testrun, the base fuel was completely drained out from the fuel tank, fuel pump and lines, and was replaced by test fuels. Further, beforecommencing the experiment, the lubrication oil and cooling watertemperature were noted to ensure whether the engine has reachedwarm up condition. The engine was loaded from 20% to 100%, progressively in steps of 20% by controlling the current supplied to theeddy current dynamometer. When changing the engine load, therack position of fuel pump is adjusted to regulate the suppliedfuel so that a constant speed of 1500 rpm is maintained. Further, suitable blends of pine oil with POME such as B25P75, B50P50,B75P25 and B100 (POME – 100%) were prepared by constant stirringand were tested in diesel engine. All the readings, pertaining to theengine experimentation and investigation, were noted down atambient conditions, when the engine was stabilized and has attained steady state condition. The experiments are repeated forthree times and average value of the readings were taken, and usedfor calculations to enhance the accuracy of the obtained results.

RESULT AND DISCUSSION

Emission characteristics

The variation of HC emission with respect to load, as shown inFig. 4, admits the fact that HC emission increases with the increasing load for all blend fuels due to increased fuel to air equivalence ratio. Noticeably, the HC emission for all the pine oil–POME blends arehigher than diesel at lower loads, while at higher loads, only B25P75and B50P50 showed decreased HC emission. However, regardless ofthe loading condition, B100 or blend fuel with higher concentrationof POME showed increased HC emission. This is because, POME has anobvious higher viscosity compared to diesel and pine oil, and therefore, the fuel atomization, evaporation and subsequent combustionprocess will be deteriorated. However, for B25P75 and B50P50, thelower viscosity of pine oil partially compensates the negative impact of higher viscosity of POME and therefore, HC emission is14.9% and 8.1% lower for B25P75 and B50P50, respectively, thandiesel at full load condition. Further, the other potential reasonsfor this reduction in HC emission for B25P75 and B50P50 at full loadcondition are (1) the fuel to air equivalence ratio approaches 1, sothe excess oxygen present in pine oil and POME is favorable forachieving a more complete combustion; (2) superior evaporation rate of pine oil and subsequent mixing of fuel with air promote abetter combustion. In the other hand, the higher HC emission forpine oil–POME blends, at lower load, could be attributed

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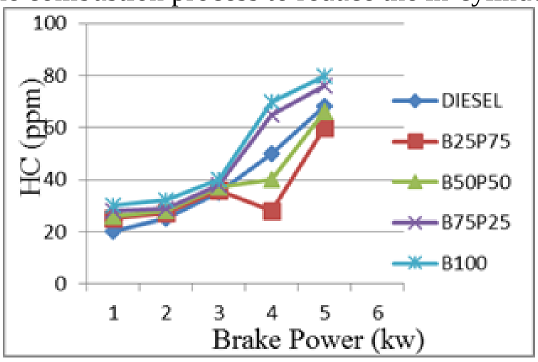
to lower fuelto air equivalence ratio, while the presence of excess oxygen atomsin both pine oil and POME will further bring down this value.

Fig.5 describes CO emission pattern for pine oil–POME blendsand diesel under various engine loading conditions. From the figure, the CO emission for B25P75 and B50P50 was found to be43.2% and 18.9% lower than diesel, at full load condition. Thisreduction in CO emission at higher loads is due to more completecombustion and better oxidation of CO to CO2, governed by abundance of oxygen in the blend fuel. Further, the surface temperatureof the combustion chamber, as the load increases, happens to getincreased and this facilitates CO oxidation. Apparently, at lowerloads, the CO emission for all pine oil–POME blends is noted tobe higher than diesel due to the reasons described above. The reported higher CO emission at lower load and subsequent reductionof it, with the increase in load, is in accordance with the results of Devan and Mahalakshmi, while testing eucalyptus oil–paradiseoil methyl ester blend in a diesel engine.One important parameter that represents the emission behaviorof a diesel engine is smoke emission. Ethanol and other less viscousfuels such as methanol or eucalyptus oil, when being used in dieselengine, has greater potential to reduce the smoke emission due totheir better fuel properties. In the same token, the reduced viscosity of B25P75 and B50P50 assists in better atomization and mixingof the fuel and by which, the smoke emission, as noticed fromFig. 6, was found to be 33.4% and 12.5% lower than diesel, respectively, at full load condition. Meanwhile, owing to the longer ignition delay for B25P75 and B50P50, the premixed combustion ismore pronounced, allowing the soot particles to combust in theoxygen rich environment, which is in concordance with the findings of Anand et al., wherein, methanol and biodiesel wereemployed as double biofuels. Further, according to the reports of Puhan et al., the smoke intensity can be reduced when the fuelis partially oxygenated, as the occurrence of fuel rich zones are reduced. In connection with this, the oxygen proportions of pine oil–POME blends are expected to be more, which in turn has reducedthe smoke emission for B25P75 and B50P50. However, forB75P25 and B100, despite the presence of enough oxygen, thehigher viscosity of POME has deterred the oxidation of soot andthereby, increasing the smoke emission.The high flame temperature, advanced injection timing andignition delay are considered as the main contributors for NO_X formation. From Fig. 7, it could be perceived that the NO_xemission for B25P75 at lower loads is decreased than diesel due tolean burning. Generally, at lower loads, the amount of fuel beinginjected is lower and this together with the induction of oxygenfrom both pine oil and POME reduces the fuel to air equivalence ratio, affecting the combustion process to reduce the in-cylindertemperature andNOXreduced.



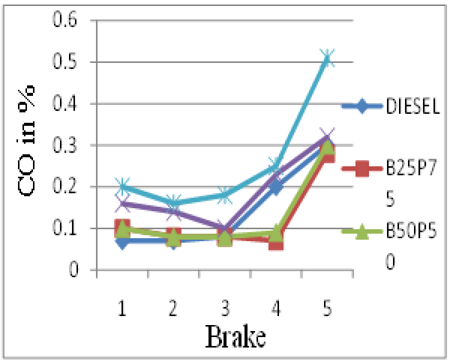
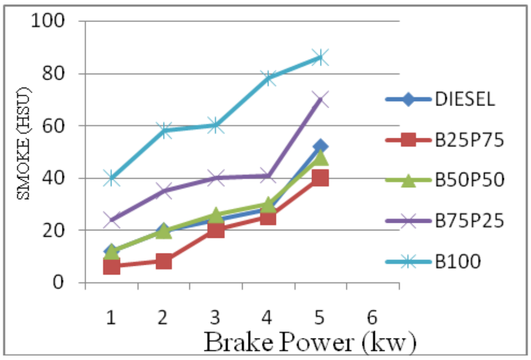


Fig.4. HC emissions for various blend fuels **Fig.5. CO emissions for various blend fuels**



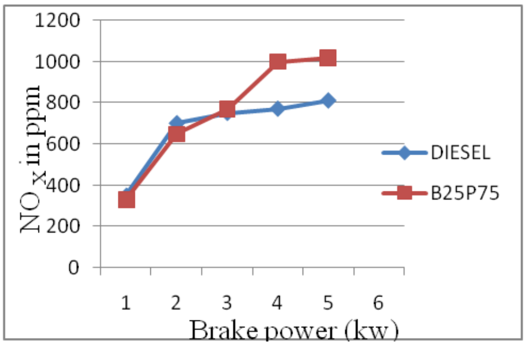
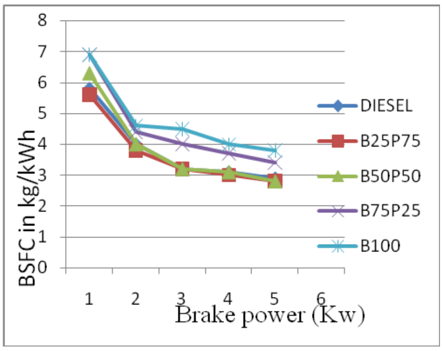


Fig.6. Smoke emissions for various blend fuels **Fig.7.NO_x emissions for various blend fuels**

However, at higher loads, the ignition delay for blends with high percentage of pine oil, as seen from heat release curve (Fig. 2), isperceived to be longer and this has prompted higher heat releaserate, increasing the in-cylinder temperature. On account of this, the NOX emission for B25P75 was observed to be higher than dieselby 10%, however, B50P50 showed a comparable NOXemission withdiesel owing to the comparable heat release rate of it with diesel.Earlier, the increase in in-cylinder temperature by virtue of morefuel being burnt in premixed combustion is noted by Qi et al. when using less viscous ethanol fuel, confirming the resultsconfronted for B25P75. However, for blends with higher proportionof POME (B75P25 and B100), the combustion is affected due to thehigher viscosity and lower calorific value of POME, resulting in reduced NOXformation.Lower the EGT better is the combustion process and higher isthe performance of the engine. As seen from Fig. 8, B25P75and B50P50 shows a decreased EGT compared to B75P25 andB100 due to better combustion, despite the longer ignition delay, manifesting no after burning in the tail pipe. The lower EGT forB25P75 and B50P50, which is an indication of reduction in energylosses to the exhaust, signifies the conversion of available energyinto useful work. With the increase in proportion of POME in theblend, the combustion is deteriorated and in the event of incomplete combustion and subsequent late burning in the tail pipe, the EGT was found to be higher for B100 and B75P25.

Performance Characteristics:



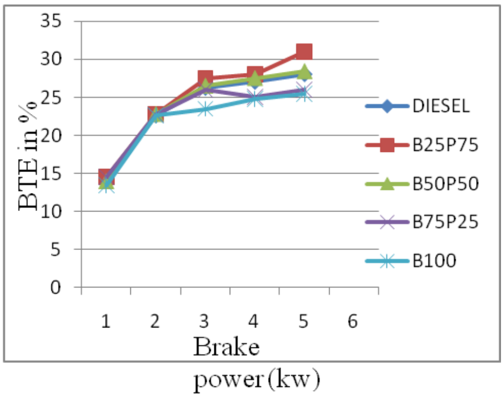


Fig.8. BSFC for various blend fuels **Fig.9. BTE for various blend fuels.**

Performance of the engine, it is imperative toinvestigate the key performance parameters such as BTE and BSFC.BSFC of the engine relies on engine design and operating parameters, and the properties of the fuel being used. Since the propertiesof pine oil are unique in that the viscosity is lower and calorificvalue is comparable to diesel, combustion is believed to be profound for B25P75 blend, resulting in reduced BSFC. FromFig. 9,itcould be inferred that BSFC for B25P75 is found to be lower thandiesel, whereas, the BSFC for B50P50 is comparable to diesel.Moreover, the combined properties of pine oil and POME is conducive for B25P75 and B50P50, as the higher viscosity and lowercalorific value of POME is believed to be compensated by therespective enhanced properties of pine oil. In previous studies onethanol–biodiesel blends, with the increase of ethanol, the fuelconsumption has been reported to be higher than diesel, as theenergy density of both ethanol and biodiesel is lower.Asopposed to this, this study has shown no compromise in BSFC forB25P75 and B50P50 due to the better calorific value of pine oil.On the other hand, when B75P25 and B100 were tested in diesel engine, the BSFC is observed to be poor, at an inverse trend of B25P75.

This is due to the lower calorific value of POME, which necessitateslarger amount of fuel injection in order to produce the same poweroutput.Similarly, BTE of the engine for different pine oil–POME blends,as envisaged from Fig. 10, shows an improvement in BTE forB25P75 and B50P50 than diesel due to better atomization andfuel/air mixing process. Analogically, Senthil Kumar et al.Pointed out increased atomization, vaporization and combustionof Jatropha methyl ester–methanol blends, owing to the reductionin viscosity of the blend with the addition of methanol. Further, theinherent presence of oxygen within pine oil and POME, along withthe superior evaporation and air/fuel mixing, has helped to attaina more active combustion, increasing the BTE of the engine.However, the BTE of the engine is lower for B100 and B75P25 thandiesel, as the higher viscosity of these blends affects the fuel atomization and predominates the combustion process.

CONCLUSION

The current work has attempted to use double biofuel, pine oil–POME blends, in a diesel engine and thereby, exclude the use of fossil diesel completely. By this measure, though the properties ofboth the biofuels are unique, the properties of the resultant blendsare found to be mutually agreeable and conducive for operation in a diesel engine. From the experimental investigation, it was understood that BTE of the engine was increased by 8% for B25P75 thandiesel at full load condition. Despite the lower HC, CO and smokeemission for B25P75 than diesel by 14.9%, 43.2% and 33.4%, respectively, it suffers the set back of higher NOXemission, owing to higher peak heat release rate. Moreover, at higher loads, the engine isprone to knocking and hence the adaptability of B50P50 for itsoperation in diesel engine is more amenable than B25P75. Notably,the BSFC and BTE for B50P50 was

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observed to be in agreement withdiesel, whereas the emissions such as smoke, HC and CO werefound to be 12.5%, 8.1% and 18.9% lower than diesel, with a comparable NOXemission with diesel. Thus, from the study, B50P50 couldbe regarded as an optimum blend among all the blends consideredin respect of all factors such optimum properties attained, comparable performance with diesel and reduced engine emissions. Foreseeing the utilization of B50P50 for long term in a diesel engine, there might arise some durability issues like injector clogging orsoot deposition due to the longer hydrocarbon chain length andmolecular weight of biodiesel. To avert this, in future, few additivescould be added with the reported blend and can be operated in adiesel engine for longer duration and finally, the injector and otherparts, can be examined for any tangible soot depositions. On theother hand, the tri-biological characteristics such as wear and corrosiveness can be ascertained for the operation of B50P50, whichcan accomplished by visualizing the lubricating oil for any visibleworn out components or rust, after running the engine for prolonged duration.

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Fig. 9.BSFC (brake specific fuel consumption) of the engine for various blend fuels.Fig. 10.BTE (brake thermal efficiency) of the engine for various blend fuels.R. Vallinayagam et al. / Applied Energy xxx (2013) xxx–xxx 7Please cite this article in press as: Vallinayagam R et al. Pine oil–biodiesel blends: A double biofuel strategy to completely eliminate the use of diesel in adiesel engine. Appl Energy (2013),http://dx.doi.org/10.1016/j.apenergy.2013.11.025

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