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Impact of pine oil biofuel fumigation on gaseous emissions from a diesel engine

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ABSTRACT

This study aims to investigate the emission reduction potential of pine oil, a plant based bio-fuel, when fumigated in a single cylinder diesel engine. Despite the feasibility of using pine oil as a potential candidate for diesel engine application, big revelation has not been made on its utility in a diesel engine. Therefore, we embarked on a research work to capitalize the renewable source of energy from bio-derived fuel, pine oil, which is much greener to the environment. Pine oil, an oxygenated fuel, possesses lower viscosity, boiling point and flash point, similar to other plant based fuels like ethanol and eucalyptus oil. However, due to its lower cetane number, the operation of it in a diesel engine demands ignition support and the lower viscosity of it necessitates modification with the fuel injection system to avert long term durability issues. Therefore, contrary to the regular method of using biofuels in blends with diesel, this study has attempted to fumigate pine oil in the inlet manifold while diesel was injected through the main injection system. By this measure, homogenized pine oil/air mixture was inducted into the cylinder and ignited by the auto-ignition of diesel. From the experimental investigation, it has been observed that pine oil can replace diesel up to 60% and 36%, at low and full load conditions, respectively. Significantly, smoke emission has been drastically reduced by 64.2% than normal diesel operation at full load condition, with a slight increase in NO_X (oxides of nitrogen) emission. Moreover, CO (carbon monoxide) and HC (hydrocarbon) emissions have been found to be 67.5% and 47.8% lower than that of diesel at full load condition. On the other hand, CO and HC emissions were noted to be increased at low load condition; however, the RAE (relative average emission) of HC, CO and smoke was found to be reduced.

1. Introduction

Diesel engine, being used as one of the vital prime movers for generating power and electricity in many industrial and agricultural applications [1], is systematized for diesel fuel operation; however, its characteristics, while using an alternate renewable biofuel, are quite different. Normally, biofuels such as alcohols, biodiesel and ethers are endowed with distinct fuel properties, which affect the fuel atomization, evaporation, mixing with air, ignition and combustion. In addition, besides the engine operating and design conditions, the type of fuel being used has an impact on engine emissions, which have been reported to be lower when using biofuels [2]. Though many researchers have agreed on using biofuels in diesel engine [3–6], their long term use is expected to cause durability and reliability problems. It is, therefore, imperative to arrive at a rational solution and foresee the existing as well as the emerging biofuels as viable alternate fuels for diesel engine without yielding to durability issues. Though some lower proportions of biofuel could be blended with diesel and used in the existing diesel engine [7], the possibility of using them in larger proportions without any long term issues entails some modifications either with the engine fuel injection system [8] or the fuel properties themselves [9].

Amidst the prevalence of many biofuels, one specific type of biofuel that has grabbed the attention of researchers is plant based biofuel that is synthesized from parts of plants such as leaves, woods, stems and resins. Thus far, such plant based bio-fuels considered and investigated for their use in a diesel engine are ethanol, eucalyptus oil, and pine oil [10,11,12]. Incidentally, these fuels have similarity in some of their thermo-physical properties, with their viscosity, boiling point, cetane number, surface tension and flash point being noted to be lower than those of diesel. However, they do have some distinct properties of their own and clearly demarcate from each other due to the differences in their origin and inherent nature. Significantly, among the plant based fuels, the calorific value of ethanol is much lower than that of diesel and produces cooling effect due to its higher latent heat of vaporization. On the other hand, eucalyptus oil and pine oil have comparable calorific value with that of diesel, while their latent heat of vaporization is not much higher than that of diesel.

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The operation of plant based fuels can be accomplished by using them either in blend with diesel or in dual fuel mode with some engine modifications. The former technique is regarded as the simplest one, while the latter entails either injection or fumigation of them in the inlet manifold. Despite the investigation of these less viscous plant based fuels in blend with diesel, the addition of them with diesel has been recommended to be in lower proportion only, as they are prone to separation problems [13,14] or if the fuel is readily mixed with diesel, it may cause injector leak or pump wear in the long term [15,16]. However, dual fuel mode of operation can overcome these limitations and has a lot of advantages over the blend fuel mode. Notably, there have been reports about the larger replacement of diesel by these fuels when being operated in dual fuel mode, especially ethanol has been used up to 75% in a diesel engine [17]. There are several ways by which dual fuel operation can be realized such as fumigation, dual injection and so on, each having certain merits and demerits in their own accord. Ajav et al. [18] vaporized ethanol in the inlet manifold of a diesel engine by using a solex-down draught carburetor and supplied ethanol–air mixture into the engine. Similarly, Chauhan et al. [19] achieved ethanol fumigation by using a simple carburetor in a small capacity diesel engine. In their study, the flow rate of ethanol was fixed constant and only the quantity of diesel being injected through the main injection system is varied with the change in load to maintain a constant speed of 1500 rpm. In another work, Goldsworthy [20] used an electronic injection system to inject ethanol and notably, the injection is made before the turbocharger so that the compressed hot air facilitated the vaporization of ethanol.

The above discussion gives some insight on the use of certain plant based biofuels in a diesel engine either by fumigation or dual fuel injection. However, it is noted that, lesser attention has been paid to utilize pine oil extensively in a diesel engine, despite being a renewable plant based fuel. In our previous study, we have used pine oil in blend with diesel, wherein, the lower cetane number of pine oil was compensated by diesel [12]. Though pine oil could be readily blended with diesel, the operation of it in blend with diesel is expected to cause durability problems in the long term. Therefore, instead of using them in blend with diesel, in another study, we fumigated pine oil and inducted vaporized mixture of pine oil and air into the engine cylinder by incorporating an engine modification technique [21]. Notably, the inlet air was preheated to 150 °C and pine oil was injected in the inlet manifold while diesel was injected through main fuel injection system, which happens to support the auto-ignition of pine oil. However, in the previous study, only the performance and combustion characteristics of the engine fumigated by pine oil at different flow rates were documented, while the gaseous emissions were not reported. It is well noted that pine oil has a greater potential to reduce the engine emissions when being used in blend fuel mode; however, the prospects of emission reduction in dual fuel mode have not been reported so far. To address this, in this study, an experiment was carried out for three different flow rates of pine oil being injected in the inlet manifold and the major emissions such as CO (carbon monoxide), HC (hydrocarbon), smoke, NO_X (oxides of nitrogen), and O_2 (oxygen) were measured. Finally, the emission reduction potential of pine oil biofuel, by virtue of its unique fuel properties and operation mode, has been elucidated with respect to diesel.

2. Fuel characterization of pine oil biofuel

In general, pine tree, widely grown for its bark, wood, turpentine, tar and essential oil, can grow up to 40 m. The essential oil obtained from pine tree is called pine oil, which is pale yellow in color, and has a fresh forest smell. There are three different varieties of pine oil known as gum, wood and sulfate pine oil, each being produced from different parts of pine tree and has their own distinctions. Apparently, a pine tree can deliver an average of 2.75 kg of pine oleoresin, which contains 20% turpentine and 65% rosin, and the turpentine present in it is used as a raw material for producing pine oil. The pine oil obtained from the resin ducts of living pine tree is called gum pine oil, which is being employed in the current study.

The steps involved in the production of pine oil have been detailed in Fig. 1. The pine oleoresin is first washed and placed in a reactor surrounded by cylindrical coils, which help facilitate passing hot steam. By virtue of this, the vapors of lower boiling fraction of oleoresins are formed and these are then condensed separately to distil turpentine and water. After the separation of low boiling fraction compounds, rosin is left behind as a residue, which has the characteristics of camphor and finds applications in many industries. To synthesize pine oil, turpentine is allowed to react with ortho-phosphoric acid and at the end of the reaction, pine oil is collected as an essential oil. A gas-chromatography analysis of the synthesized pine oil exudes the presence of terpineol ($C_{10}H_{18}O$), a tertiary alcohol, and pinene ($C_{10}H_{16}$) as its major constituents. Notably, the column of the GC–MS (gas chromatography mass spectrometer) was initially heated up to 50 °C and subsequently, at the ramp rate of 2 °C/min, the temperature was raised up to 200 °C with the split ratio of 80:1. Further, helium, with a purity of 99.99%, was used as a carrier gas at the flow rate of 2 μl/min. Based on the retention time of the constituents identified, 9.768 and 8.309 s for pinene and terpineol, the mass spectra of them, depicting the molecular weight and structure, were collected from standard database and are shown in Fig. 2a and b. It is a matter of fact that pine oil has inherent oxygen in its structure, when compared to petroleum diesel. It could be noted that pine oil entails $-CH_2-$, $>CH-$, $=CH-$, $>C<$ and $=C<$ as ring group members, and $-CH_3$ as a non-ring group member with an additional alcohol ($-OH$) group. Though ethanol and pine oil could be classified as primary and tertiary alcohols, they do have certain differences in their structure and general attributes. After scrutinizing their structures, pine oil is perceived to be an alicyclic hydrocarbon with carbon, hydrogen and oxygen in its structure while ethanol is noted as an aliphatic hydrocarbon. Also, ethanol has a shorter carbon chain length whereas, it is cyclic for pine oil, both influencing the fuel properties, particularly the ignition quality of them.

The properties of pine oil, as determined by ASTM standard methods and shown in Table 1, clearly indicate lower viscosity, boiling point and flash point than those of diesel, which are expected to improve the fuel atomization, evaporation and its mixing with air. However, the cetane number of it has been noted to be lower, resulting in poor ignition quality and this is further deteriorated by its higher self-ignition temperature. As opposed to lower alcohol, ethanol (C_2H_5OH), pine oil has comparable calorific value to diesel, favoring the prospects of using it in larger proportions with diesel. Further, unlike ethanol, pine oil does not suffer higher latent heat of vaporization, thus it is not bound to cause any cooling effect, though its value is slightly higher than that of diesel. Pine oil is readily soluble in diesel and the effect of blend integrity, studied by mixing and keeping the blend for 3 months, showed no signs of visible separation. Moreover, to ensure the thermal and oxidative stabilities of pine oil, a thermo-gravimetric analysis of it was conducted, both in air and nitrogen atmosphere at the ramp rate of 20 °C/min, and is shown in Fig. 3a and b. The results of the analysis showed that pine oil is stable up to 180 °C and beyond 180 °C, there were no traces of pine oil, as noted in Fig. 3.

3. Experimental setup and procedure

A Kirloskar TV1 engine has been employed to investigate the effect of pine oil fumigation on engine emission. This engine is a typical stationary diesel engine, being used for agricultural and industrial applications, and is run at a constant speed of 1500 rpm. Further, the engine is loaded by a water cooled eddy current dynamometer in steps of 20% from 20% to 100% load. Mechanical type fuel injection pump has been used with a 3 hole nozzle-injector assembly to inject diesel, at a pressure of 220 bar and timing of 23°BTDC (before top dead center),