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Availability analysis, performance, combustion and emission behavior of bael oil - diesel - diethyl ether blends in a variable compression ratio diesel engine

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A B S T R A C T

The aim of the present work is to experimentally investigate the effect of injection pressure (IP) and injection timing (IT) on the performance, combustion, and emissions of a compression ignition (CI) engine with aegle marmelos oil (bael oil) blends. This work includes the exergy analysis of diesel engine to maximize the work availability. The tests were conducted on a constant speed direct injection diesel engine fueled with ternary blends of bael oil, diethyl ether (DEE) and neat diesel (D) at various engine loads. When the engine was operated with B2 blend (60%D+30%bael oil+10%DEE), there was an increase in brake thermal efficiency of 3.5% accompanied by a declination in oxides of nitrogen emissions by 4.7% at full load with 250bar IP. The B2 blend showed lower hydrocarbon emission by 7% as compared to that of neat diesel at full engine load with fuel IT of 23° before top dead center. With Increase in engine load, augmentation exhaust gas and cooling water availabilities lead to amplification of exergy efficiency with increasing load. The exergy efficiency of B2 fuel has found as 62.17% of fuel input at 230bar IP with 100% load. From results, B2 fuel exhibits the best performance and combustion characteristics.

1. Introduction

The combustion of fossil fuels in internal combustion (IC) engines is one of the major sources of air pollution and fossil fuel depletion. Biofuels are one of the most effective solutions for a global warming reduction and fuel needs [1,2]. In developing country like India, the requirement for diesel fuel is around six times more than that of gasoline. Subsequently, the search for the alternative to neat diesel is becoming inevitable and most of the nations spend an enormous part of trade profit on acquiring crude petroleum from other nations [3,4]. Straight vegetable oils (SVO) obtained from plant seeds/harvests can be utilized directly in diesel engines without any engine modifications. Vegetable oils and alcohols that can be derived from biomass are imperative substitute fuels for use in diesel engines [5–7]. In general, kinematic viscosity of SVO does not meet the necessities ASTM D396 standard, which sets a limiting value of 2–3.6 centistokes (cS) at 40 °C and is 10–15 times higher than that of diesel [8–10]. Micro-emulsification is one of the easiest and cost-effective processes used to blend two liquid fuels by using butanol, DEE, octanol or hexanol as a surfactant [11,12]. It is a general technique to decrease the viscosity of alternative fuel blends to the required level in order to facilitate fuel injection. Furthermore, certain solvents can be blended with vegetable oils to give a stable performance at lower temperatures [13]. The peak heat release showed by SVO is lower than that of the fossil diesel fuel and emits considerably lower oxides of nitrogen (NOx) emissions, higher carbon monoxide (CO) and hydrocarbon (HC) emissions [14–16]. Basic and simple ideas to overcome these problems are to blend the SVO with diesel fuel; however, test result shows high carbon deposits in the engine, piston ring sticking, injector coking, lubrication oil thickening as an after effect of dilution and polymerization [17,18]. The reduction in ignition delay and peak cylinder pressure, and an increase in combustion period are observed for diesel and SVO blended with oxygenated additives [19,20]. At the point when DEE composition increased over 24%, heavier smoke was observed [21]. The utilization of DEE has added a few constraints, such as lower lubricity, higher unpredictability and lower miscibility which may increase unburned HC emissions [22,23].

The first law of thermodynamics does not consider the quality of energy content of a system whereas the second law of thermodynamics diagnoses losses and provides solutions for enhancing

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engine performance and engine efficiency [24]. Exergy investigation contributes for planning more effective thermal system and to diminish inefficiencies in thermal systems [25]. Exergy losses to unburned species increased considerably at lower equivalence ratio [26,27]. Azoumah Y et al., investigates the exergy analysis combined with gas emission analysis for the compression ignition (CI) engine fueled with biofuels [25]. Advancing of injection timing reduces the NOx emission sharply by the lower peak combustion temperature. Then again, an increase in smoke opacity was observed as a result of retarded injection timing [28,29]. Further retardation of injection timing leads to augments HC emission in naturally aspirated diesel engines. The increase in injection pressure resulted in higher NOx and CO_2, and decreased opacity emissions [30].

Aegle marmelos is a tree native to India which is generally growing wild in sub-Himalayan tracts, West Bengal also found in central and south India. The bael seeds were collected from the Eastern Ghats of Tamil Nadu, India and bael oil is extracted from the bael seed using the mechanical press. It is grown all over India, predominantly in sanctuary gardens because of its status as a sacred tree; likewise northern Malaya and Srilanka [29]. Aegle marmelos is a moderate growing, medium-sized tree; grow up to 12–15 m, which has a place with *rutaceac* family. The bael core seeds yielded 49% oil during extraction. The seed oil has 12.5% of 12-hydroxyoctadec-cis-enoic acids alongside other normal fatty acids [3]. It copes up with a wide range of soil conditions (pH range 5–10) and it is tolerant to water logging and has unusually wide temperature resilience (0 °C–50 °C). The organic fruits are 5–7.5 cm in diameter, elongated pyriform in shape, with a dark or yellow skin. The seeds (fifty or more in a fruit) are implanted in a thick gummy pulp. The seeds were dried overnight at 55 °C in an oven to eliminate excess moisture. The dried seeds were weighted and powered. The resulting bael seed oil is light yellow in color. The properties of bael oils are iodine value - 94 mg iodine/g; saponification value −205 mg/KOH; higher heating value (HHV) - 40.04 MJ/kg; lower heating value (LHV) −33.27 MJ/kg [30].

In this paper, effects of IP and IT are taken as operating parameters and the diesel engines performance, combustion, exhaust emissions and exergy analysis has been investigated in the VCR engine with bael oil blends. The second objective is to find the appropriate input parameters to the CI engine for optimal output behaviors such as performance, emissions, and exergy efficiency for specified fuel blends and diesel.

2. Materials and methods

2.1. Fuel properties

The flash point and fire point, density, and kinematic viscosity are determined for different fuel blends according to ASTM D-93, ASTM D-1298, and ASTM D-445 respectively. The DEE of 99% purity purchased from neighborhood business agent. Bael oil is mixed with diesel and DEE in a blender unit and stirred at 500 rpm for 20 min and left for 30 min to reach equilibrium at room temperature before the experimental test. Ternary blends of diesel fuel(D) – bael oil (SVO) - Diethyl ether (DEE) as percentages (vol. %) of 70% D −20%SVO-10%DEE (B1), 60%D-30%SVO-10%DEE (B2), 50%D-40% SVO-10%DEE (B3) were selected in the soluble area of ternary phase. The feasible blending ratio of vegetable oil to neat diesel is lies between 20 and 40%. The addition of fuel additives has improved the ignition performance and reduces the exhaust emissions. The phase separation of the fuel blends results that cavitations in the fuel line and injector nozzle if more than 15% of DEE to diesel. The erratic combustion takes place the DEE addition more than 24% in blends [56]. The erratic combustion takes place the DEE addition more than 24% in blends. The flash and fire points are determined by Pensky Martin closed cup fire point apparatus. The kinematic viscosity is measured by the redwood viscometer. The properties of diesel, bael oil and DEE and its blends are given in Tables 1 and 2. The ignition performance of fuel is of crucial importance for CI engines as insufficient ignition quality can lead to higher emissions. The cetane number (CN) is widely used for indicating the ignition performance and is arrived with the following formulae according to the volumetric concentration of each constituent [3]:

(1) Cetane number $CNH = \sum_i CN_i X_i$

(2) Calorific value $CVH = \sum_i CV_i X_i$

Where CNH, CVH are the equivalent cetane number, calorific value of the blended fuel, while CNi is the cetane number of each constituent, Xi is the percentage of constituents and CVi is the calorific value of each constituent.

2.2. Experimental setup and procedure

To evaluate the performance and emissions of the test fuels and compare with diesel fuel, the experimental runs were conducted in a single cylinder direct injection variable compression ratio (VCR) test engine. The engine used for the test was a Kirloskar VCR and specifications are shown in Table 3. The fuel injection pressure (IP) is varied by 210bar, 230bar, and 250bar, and the fuel injection timing (IT) varied by 21°, 23° and 25° before top dead center (bTDC) and the injector has three nozzle holes located near the combustion chamber center. The injection pressure was taken as 210bar, 230bar, and 250bar. When using lower IP (below 210bar) for vegetable oil blended fuels in compression ignition engines, more unburned hydrocarbon and smoke opacity were observed due to inefficient atomization [28]. If using higher IP (250bar and above) caused elevated unburned hydrocarbon and soot due to wall quench of fuel particle which can be attributed to higher momentum of the fuel particles that hit the combustion chamber wall and piston crown surfaces [29]. The engine was connected to an eddy current dynamometer and suitable arrangements were made to acquire all the controlling parameters. HC, CO_2, NOx and CO emissions were measured with the aid of Exhaust gas analyzer AVL DI 444 model (Table 4). Smoke opacity is measured with the aid of Smoke meter, model AVL437C (Table 5). The piezoelectric transducer (Kistler make) is positioned within the cylinder head and is used for measuring in-cylinder pressure measurement. Piezoelectric pressure transducers are suitable for measuring highly dynamic, dynamic and quasi-static pressure curves or pulsations. The flush mounted technique is used to fasten the transducer on the cylinder head to avoid passage effects. Signals from pressure transducer are fed to charge amplifier. The signals from crank angle encoder and charge amplifier are acquired using data acquisition system (DAQ). The device is ideal for test, control and design applications including portable data logging, field

Table 1
Properties of diesel, bael oil and DEE.

Property	Diesel	Bael oil	DEE
Element structure	$C_{16}H_{34}$	$C_{18}H_{36}O_2$	$C_2H_5OC_2H_5$
Density (kg/m^3)	830	896	713
Viscosity (cS)	2.7	24.3	0.23
Auto ignition point (°C)	200–400	<370	160
Cetane number (CN)	50	51.7	>124
Pour point (°C)	−20	−5	−110
Fire point (°C)	52-96	260	35
Lower heating value (kJ/kg)	42800	36300	33900
Chemically correct A/F ratio	14.9	12.4	11.1