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Effect of antioxidant on the performance and emission characteristics of a diesel engine fueled with palm biodiesel blends

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ABSTRACT

Biodiesel is a clean-burning alternative fuel produced from renewable resources. However, it is susceptible to oxidative degradation due to autoxidation in the presence of oxygen, which hinders its widespread use. Antioxidant addition is a prospective solution to this problem. It is expected that antioxidants may affect the clean-burning characteristic of biodiesel. Palm biodiesel (PME) is the most used biodiesel in Malaysia. This paper presents an experimental investigation of the effect of antioxidant addition to palm biodiesel on engine performance and emission characteristics. PME was produced by transesterification using potassium hydroxide (KOH) as catalyst. Two monophenolic antioxidants, 2, 6-di-tert-butyl-4-methylphenol (BHA) and 2(3)-tert-butyl-4-methoxy phenol (BHT), were added at 1000 ppm concentration to 20% PME (B20) to study their effect. The addition of antioxidants increased oxidation stability without causing any significant negative effect on physicochemical properties. BHA showed greater capability to increase the stability of B20. A 42-kW, 1.8-L, four-cylinder diesel engine was used to carry out tests under conditions of constant load and varying speed. The results show that B20 and antioxidant-treated B20 produced 0.68–1.02% lower brake power (BP) and 4.03–4.71% higher brake specific fuel consumption (BSFC) compared to diesel. Both of the antioxidants reduced NOx by a mean of 9.8–12.6% compared to B20. However, compared to B20, mean increases in carbon monoxide (CO) and hydrocarbon (HC) emissions of 8.6–12.3% and 9.1–12.0%, respectively, were observed. The emission levels of the three pollutants were lower than those of diesel. Thus, B20 blends with added antioxidant can be used in diesel engines without any modifications.

1. Introduction

Significant population growth and changes in lifestyle are resulting in ever-increasing consumption of energy. The main consumers of energy are the electricity generation and transportation sectors. The diesel engine forms a vital part of both of these sectors throughout the world. Diesel fuel has versatile applications because of its high fuel efficiency compared to gasoline. Increasing fossil oil prices, limited reserves of fossil fuels, and environmental concerns have boosted the research on alternative fuel sources such as biodiesels. Moreover, global carbon dioxide (CO_2) emissions from fossil-fuel combustion are increasing every year, intensifying air pollution and magnifying the global warming problems caused by CO_2 [1]. Diesel vehicles are a significant source of nitrogen oxides (NOx) and particulate matter (PM) [2]. High PM concentration in ambient air causes degradation of lung function, cardiovascular diseases, irregular heartbeat, neurodegenerative disorders, and heart attacks [3]. When inhaled, CO replaces oxygen in the blood stream so that the body's metabolism cannot function properly. NOx causes lung irritation and deteriorates resistance to respiratory infection. NOx is one of the important precursors of acid rain, which disturbs both aquatic and terrestrial ecosystems. Thus, air pollution caused by engine emissions has serious physical and environmental effects.

Biodiesel, designated as B100, is defined as mono-alkyl esters of long-chain fatty acids (FAs) prepared from plant oils, animal fats, or other lipids [4]. The advantages of biodiesel over petroleum diesel fuel include derivation from renewable feedstocks, superior lubricity and biodegradability, lower toxicity, essentially no sulfur or aromatic content, higher flash point, positive energy balance, and reduced emissions [5–7]. On the other hand, biodiesel has a higher level of olefinic components, which are corrosive and can attack metals, which can be attributed to the presence of oxygen moieties, auto-oxidation, increased polarity of biodiesel, and its hygroscopic nature [8].

Malaysia is the world's second largest producer and exporter of palm oil after Indonesia [9]. Malaysia currently accounts for 39% of world palm oil production and 44% of world exports [10]. The use of biodiesel produced from palm oil reduces the country's

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Nomenclature

ASTM	American Society for Testing and Materials	UHC	Unburnt hydrocarbon
BHA	2,6-di-tert-butyl-4-methylphenol	IDI	Indirect Injection
BHT	2(3)-tert-butyl-4-methoxy phenol	IV	Iodine Value
BP	Brake Power	PME	Palm Methyl Ester
BSFC	Brake Specific Fuel Consumption	NDIR	Non-dispersive Infrared
BTE	Brake Thermal Efficiency	NOx	Nitrogen oxides ($NO+NO_2$)
CLD	Chemiluminescence Detector	SN	Saponification Number
CN	Cetane Number	B0	Diesel
CO	Carbon monoxide	B100	Palm biodiesel/PME
FAC	Fatty Acid Composition	B20	20% PME + 80% B0
FID	Flame Ionization Detector	B20 + BHA	20% PME + 80% B0 + 1000 ppm BHA
FRIM	Forest Research Institute Malaysia	B20 + BHT	20% PME + 80% B0 + 1000 ppm BHT
GC	Gas Chromatography		

dependence on foreign oil [11]. This study focuses on a 20% blend of palm oil methyl ester to promote the use of a higher percentage of biodiesel blends, since mandatory use of B5 is now in effect in different states of Malaysia. Moreover, use of biodiesel in blended form does not require extensive engine modifications or changes in the fuel handling and delivery systems [12].

1.1. Objectives of the study

In the present study, palm oil methyl was produced via alkali-catalyzed transesterification of palm oil purchased from the Forest Research Institute Malaysia (FRIM). The effect of the addition of two antioxidants – 2,6-di-tert-butyl-4-methylphenol (BHA) and 2(3)-tert-butyl-4-methoxy phenol (BHT) – on the basic fuel properties of B20 was investigated and compared with ASTM D7467 for diesel–biodiesel blends. The influence of these antioxidant additives on the engine performance and emission characteristics of an indirect injection turbocharged diesel engine fueled with B20 blends was also investigated. The performance and emission results were compared with untreated B20 as well as diesel fuel.

1.2. Literature review

Many researchers have investigated the application of PME and its blends on the performance, emissions, and combustion characteristics of diesel engines. Ozsezen et al. studied the performance, injection, and combustion characteristics of a four-cylinder IDI diesel engine using used frying palm oil and its blends with diesel fuel over a range of engine speeds at full load [13]. They found lower brake torque and power with increases in the amount of biodiesel in the blend due to the lower energy content of the biodiesel, which in turn resulted in a higher BSFC for blends. They also found decreasing thermal efficiency with increases in the amount of biodiesel in blends. Combustion curves show that the start of injection of biodiesel and its blends was earlier than that of diesel due to the higher density, viscosity, and compressibility of the fuel. Zhu et al. tested 5% and 20% v/v PME in a Cummins DI diesel engine fitted with a turbocharger and intercooler [14]. The use of biodiesel blends leads to an increased BSFC but almost the same level of BTE compared to baseline diesel fuel. Biodiesel blends gave a remarkable decrease in smoke opacity (28.8%) but higher NOx emission (8%). Vedaraman et al. [15] studied the effect of different blends of palm biodiesel with diesel on engine performance and emission characteristics and found B20 to be the optimum blend in terms of higher thermal efficiency and lower NOx emission. B20 also produced about 28% and 30% lower CO and HC emissions compared to baseline diesel, respectively. Ng et al. [16] evaluated the suitability of PME-based biodiesel and its blends for on-road usage. They observed a reduction of tailpipe NO, UHC, and smoke opacity when neat PME was used, with maximum decreases of 5.0%, 26.2%, and 66.7%, respectively.

Biodiesel degrades mainly due to its autoxidation in the presence of atmospheric oxygen. The result of the process of oxidation of biodiesel is the formation of hydroperoxides (ROOH) [17]. Once the hydroperoxides have formed, they are decomposed and then inter-react to form numerous secondary oxidation products. These consist of higher molecular-weight oligomers, often termed polymers. One practical solution to lower the resistance of biodiesels against autoxidation without significantly modifying the fuel properties is to treat them with antioxidants (AH) [18]. Antioxidants significantly slow down the biodiesel degradation process. According to their mode of action, antioxidants can be classified into various groups: free-radical terminators, metal-ion chelators capable of catalyzing lipid oxidation, or oxygen scavengers that react with oxygen in closed systems. Free-radical terminators are considered primary antioxidants; they react with high-energy lipid radicals and convert them into thermodynamically more stable products [19]. Both phenolic and amine antioxidants are the most used antioxidants. They are recognized as free radical terminators. Both of the antioxidants used in this study, that is, BHA and BHT, are phenolic-type antioxidants. Secondary antioxidants work by impeding the rate of chain initiation by decomposing the hydroperoxides. The free-radical terminators contain a highly labile hydrogen, which is rapidly donated to a peroxyl radical ($ROO^{\cdot}$), which interferes with the lipid-oxidation process [Reactions (1) and (2)] [20]. The term, "stabilization factor" is often used to denote the effectiveness of an antioxidant and is expressed as $F = IP_x/IP_o$, where IP_x is the induction period in the presence of the antioxidant and IP_o is the induction period in its absence [21].

$$ROO^{\cdot} + AH \rightarrow ROOH + A^{\cdot} \tag{1}$$

$$RO^{\cdot} + AH \rightarrow ROH + A^{\cdot} \tag{2}$$

Hess et al. [22] studied the effect of the addition of different antioxidants to 20% soy biodiesel on NOx emission and found that it was reduced by the addition of BHA and BHT. Kalam and Masjuki studied the effect of 4-nonylphenoxy acetic acid (NPAA) on engine emissions and found 20%, 71%, and 17% reductions of NOx, CO, and HC emissions, respectively [23]. Ryu [24] studied the effect of antioxidant addition to soybean biodiesel. Tert-butylhydroquinone (TBHQ) was the best stabilizer among the five antioxidants tested. Engine combustion, performance, and emission analyses were performed while varying the contents of TBHQ and PG (propyl gallate). With TBHQ, there was no significant change in smoke, HC, or NOx compared to the untreated fuel. Kivevele et al. [25] reported that biodiesel dosed with antioxidant PY showed a lower BSFC