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Analysis of blended fuel properties and cycle-to-cycle variation in a diesel engine with a diethyl ether additive

Obed M. Ali [a,*], Rizalman Mamat [a], H.H. Masjuki [b], Abdul Adam Abdullah [a]

[a] Faculty of Mechanical Engineering, Universiti Malaysia Pahang, 26600 Pekan, Pahang, Malaysia
[b] Centre for Energy Sciences, Faculty of Engineering, University of Malaya, 50603 Kuala Lumpur, Malaysia

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ABSTRACT

In this study, the effect of adding small portions of a diethyl ether additive to biodiesel–diesel blended fuel (B30) was investigated. This study includes an evaluation of the fuel properties and a combustion analysis, specifically, an analysis of the cyclic variations in diesel engines. The amount of additive used with B30 is 2%, 4%, 6% and 8% (by volume). The experimental engine test was conducted at 2500 rpm which produce maximum torque, and the in-cylinder pressure data were collected over 200 consecutive engine cycles for each test. The indicated mean effective pressure time series is analyzed using the coefficient of variation and the wavelet analysis method. The test results for the properties show a slight improvement in density and acid value with a significant decrease in the viscosity, pour point and cloud point of the blended fuel with an 8% additive ratio by 26.5%, 4 °C and 3 °C, respectively, compared with blended fuel without additive. However, the heating value is reduced by approximately 4% with increasing the additive ratio to 8%. From the wavelet power spectrum, it is observed that the intermediate and long-term periodicities appear in diesel fuel, while the short-period oscillations become intermittently visible in pure blended fuel. The coefficient of variation for B30 was the lowest and increased as the additive ratios increased, which agrees with the wavelet analysis results. Furthermore, the spectral power increased with an increase in the additive ratio, indicating that the additive has a noticeable effect on increasing the cycle-to-cycle variations.

1. Introduction

The development of renewable and clean energy has become an urgent endeavor to fulfill the increasing energy demand across all aspects of society, compensating for the continuous depletion of fossil fuel resources and mitigating increasing environmental pollution. Among all of the renewable fuels, biodiesel has been of primary interest due to its similar energy and chemical structure to petroleum diesel. Biodiesel is renewable, biodegradable, sustainable, environmentally friendly and carbon–neutral over its entire life cycle; it is produced by chemically reacting vegetable oil or animal fat with an alcohol [1,2].

Alternative fuels, such as biodiesel, can be used in any proportion in the existing diesel engine without any modification of the engine because they have similar combustion characteristics [3,4]. A palm oil biodiesel–diesel blend has a higher ignition temperature, shorter ignition delay and higher pressure and peak heat release compared with diesel fuel. Furthermore, the output engine power and brake power efficiency are comparable to diesel fuel. Biodiesel has been blended up to 20% with petroleum diesel as a commercial transportation fuel in a number of countries [5]. These blends are being considered as replacement options for pure petroleum diesel in many applications.

The major properties of biodiesel that restricted its application in a high blending ratio are higher viscosity, lower energy content [6–8], higher pour point and cloud point [9–11], higher nitrogen oxide (NO_x) emissions and lower engine power compared with ordinary diesel [12,13], as well as problems related to injector choking and engine compatibility [14]. The most convenient method to make biodiesel available as a fuel in a high blending ratio as an alternative to ordinary diesel is the use of chemical additives [15]. These additives mainly facilitate the reduction of emissions of nitrogen oxides, particulates and hydrocarbons and improve combustion [16].

In general, the chemical additives used have a relatively low flash point and auto-ignition temperature compared with diesel and biodiesel fuels [17], and cycle-to-cycle variations may develop when exceeding a certain limit. Furthermore, these differences might lead to a reduction in engine output power and higher emissions;

* Corresponding author.
E-mail address: obedmajeed@gmail.com (O.M. Ali).

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Nomenclature

B30	30% palm oil biodiesel + 70% diesel
IMEP	indicated mean effective pressure
COV	coefficient of variations
COVimep	coefficient of variations of indicated mean effective pressure
CCV	cycle-to-cycle variations
DEE	diethyl ether
CP	cloud point
PP	pour point
A, B and C	letters used in Tukey grouping analysis
AV	acid value
Pmax	maximum pressure
WPS	wavelet power spectrum
GWS	global wavelet spectrum
B-DE	biodiesel-diethyl ether blend
CWT	continuous wavelet transforms
COI	cone of influence

therefore, it is necessary to develop effective control strategies for the optimum additive ratio by gaining a better understanding of the various factors that affect the overall combustion process.

An oxygenated additive, such as diethyl ether (DEE), can be used with blended diesel–biodiesel fuel to reduce NO_x emissions [18]. Diethyl ether has a low auto-ignition temperature, and it is an excellent ignition enhancer [19]. DEE is considered to improve the cold starting of a diesel–water emulsion [20]. In their experimental study, Iranmanesh et al. observed that a 5% of DEE with diesel blend was the most effective combination based on engine performance and emission characteristics [21]. However, Rakopoulos et al. [22] suggested DEE as a promising fuel with mineral diesel that can be used safely in diesel engine up to high blending ratios (24% by volume) with stable engine operation [23]. Qi et al. [24] showed in their study on soybean biodiesel–diesel blended fuel B30 that with 5% of DEE, the brake-specific fuel consumption (BSFC) is slightly lower and is accompanied by a greater reduction in smoke, CO emissions and similar NO_x emissions compared with B30. However, Imtenan et al. conducted studies to investigate the impact of DEE additive with a blend of biodiesel–diesel fuel on engine performance, emission and combustion characteristics. They found that a 10% DEE showed higher improvement in engine performance and emission characteristics than 5% additive ratio with jatropha biodiesel–diesel blend B20 [25] and palm biodiesel–diesel blend B20 [26]. Many studies have investigated the blend of DEE with biodiesel as a method to reduce emissions. Diethyl ether was used at a low percentage (5% and 10%) to improve engine performance and emission characteristics with rubber seed biodiesel fuel [27] and waste plastic pyrolysis oil [28]. another study found that, the better engine performance has been obtained with the blend of Karanja oil methyl ester and 15% DEE [29]. Similarly, Sivalakshmi and Balusamy [30] found that based on engine performance and emission characteristics, 15% DEE is the optimum blend ratio with Jatropha oil methyl ester. However, they conclude in another study that 5% DEE can be a promising technique for using biodiesel efficiently in unmodified diesel engine [31]. On the other hand, in their experimental investigation, Pugazhvadivu and Rajagopan [32] showed that a 20% DEE additive was more effective at reducing NO_x with Pongamia oil biodiesel fuel compared with another combination. Similarly, in their experimental study, Kannan and Marappan [33,34] again showed that a blending ratio of 20% DEE with Thevetia Peruviana biodiesel results in better engine performance and fewer emissions than with other combinations. Another study conducted by Swaminathan and Sarangan [35] with fish oil biodiesel revealed that 2% DEE with exhaust gas recirculation (EGR) gave the maximum reduction of all of the emission pollutants with biodiesel and was suggested as the best option for operating an EGR engine.

Continuous wavelet transforms (CWT) have been an active topic of research to understand the cycle-to-cycle fluctuations for many years. Previous studies focused on spark ignition engines (SI) [36]; however, recent studies have examined diesel engines. An analysis of the indicated mean effective pressure (*IMEP*) cycle-to-cycle variations was conducted using CWT for various diesel engine speeds [37]. In this study, it is found that the pressure variations may have a strongly intermittent periodic component depending on the speed of the engine. The strong periodicities may persist over many cycles and appear in low-frequency bands, whereas at higher frequencies, the intermittency is present. Another study [38] used the same methodology to investigate the utilization of a different alternative fuel for a diesel engine and compared it with petroleum diesel.

The goal of this study is to investigate the effect of using the diethyl ether additive with the B30 blend in a diesel engine for cycle-to-cycle variation. Of additional interest was the determination of the minimum number of cycles required to mitigate the effect of cyclic variations at various additive ratios on a diesel engine.

2. Methodology

2.1. Fuel property measurement

The experimental tests were performed using diesel fuel, blended fuel B30 (30% palm oil biodiesel and 70% petroleum diesel) and B30 with diethyl ether additive at different ratios of 2%, 4%, 6% and 8% by volume. The fuel samples were prepared using an electric magnetic stirrer to ensure a homogenous fuel mixture. A digital constant temperature kinematic viscosity bath (model K23376 KV1000) was used to measure the fuel kinematic viscosity at a constant temperature of 40 °C ± 0.1, according to ASTM D-445. The fuel density measurement was conducted at 20 °C, according to ASTM D1298, using a portable density meter (model DA-130N). An acid value measurement was obtained using a Metrohm test apparatus (model 785) according to the specifications of the American Oil Chemists Society method. A Koehler apparatus model K46195 was used to measure the pour and cloud points, according to ASTM D-97 and ASTM D-2500, respectively. The flash point was measured according to ASTM D93 using a Pensky-Martens closed tester, while the cetane number was measured according to ASTM D4737-03 using a SHATOX portable octane analyzer. The fuel property measurements were conducted in a chemical laboratory under controlled environmental conditions. Furthermore, each test was performed in triplicate, and the average values were considered in the analysis to ensure results that are more accurate. A statistical analysis technique called “Tukey Grouping” was performed on the data. This technique provides specific information on the interaction between the variables. In Tukey Grouping, if the variables have the same letter, then the difference between those variables is not statistically significant. On the other hand, there is a significant statistically deference among the variables if those variables have different letters [39]. For all of the statistical analyses of this