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Deterioration of palm biodiesel fuel under common rail diesel engine operation

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A B S T R A C T

Although numerous studies have shown the adverse effects of oxidized biodiesel and/or higher total acid number (TAN) and water content in biodiesel fuel on the degradation of fuel delivery materials, limited work has been reported to date to ascertain the presence of these factors under actual engine operation. Therefore, the aim here is to determine if these factors exist under common rail diesel engine (CRDE) operation. For this, an engine test-bed comprising a Toyota 1KD-FTV engine coupled to an eddy current dynamometer was operated under two different speed-load test cycles using palm biodiesel with 10.5 h of oxidation stability according to the Rancimat test. The results indicated that the biodiesel fuel samples were not oxidized while both TAN value and water content were unaffected at the end of the CRDE operations under both the test cycles. As such, emphasis should not only be placed solely on the acceleration of fuel delivery materials degradation due to biodiesel oxidation and/or greater TAN value and water content under engine operation. This study also demonstrated that biodiesel conductivity value is a more appropriate indicator of fuel deterioration level under CRDE operation which ultimately determines the compatibility between biodiesel and fuel delivery materials.

1. Introduction

An increasing number of countries to date are adopting biodiesel as a substitute to fossil diesel to power diesel engines as shown in Supplementary Table 1 [1–6]. The major reason behind this is to reduce reliance on fossil fuels which are finite resources. Additionally, the use of biodiesel lowers the concentrations of diesel exhaust emissions such as particulate matter, carbon monoxide and unburned hydrocarbons [7] which lowers helps alleviate declining air quality. Risks to human health are also lowered since diesel exhaust emission is classified under Group 1 compounds which are carcinogenic to humans [8]. Currently, biodiesel is only used in blended form with fossil diesel at a blending level no greater than 20% vol (B20). Utilization beyond B20 could typically lead to significantly early failure of existing fuel delivery materials due to greater metal corrosion and elastomer degradation. Most importantly, loss of compression due to seal breakage and fuel leakage which results in reduced power output is typically observed. If the leakage goes unnoticed especially at the line (or hose) connecting the fuel filter and the fuel pump, the resulting fuel starvation could lead to the fuel pump to abruptly seize, forcing the engine to halt.

Fuels in general are typically required to have a minimum oxidation stability value to prevent rapid deterioration and oxidation during engine operation. This is essential since the formed oxidized products such as aldehydes, ketones and short-chain acids are known to accelerate the fuel delivery materials degradation process [9–14]. To date, in a diesel engine equipped with common rail type fuel injection system, the fuel would normally be pressurized up to 2000 bar which can lead to significantly high fuel temperatures in excess of 100 °C. High fuel temperature coupled with the presence of various materials such as copper and nitrile rubber in the fuel delivery system can catalyse the oxidation

Abbreviations: Al, Aluminium; ASTM, American Society for Testing and Materials; B100, 100% biodiesel/neat biodiesel; B20, 20% biodiesel, 80% diesel; BHT, Butylated hydroxytoluene; CEC, Co-ordinating European Council; Co, Cobalt; CRDE, Common rail diesel engine; Cu, Copper; Fe, Iron; FTIR, Fourier transform infrared spectroscopy; g, gram; ICP-OES, Inductively coupled plasma-optical emission spectrometer; Mg, Magnesium; Mn, Manganese; Ni, Nickel; Sn, Tin; TAN, Total acid number; WHSC, World Harmonized Stationary Cycle; Zn, Zinc.

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process which causes the fuel quality to deteriorate [10,15,16]. The fuel return system as shown in Supplementary Fig. 1 allows the deteriorated biodiesel fuel to be recirculated back into the storage, contaminating the fuel in the reservoir [17]. When biodiesel is used, this problem is aggravated due to its lower oxidation stability as compared to fossil diesel.

Two recommended solutions to this have been proposed, which are firstly, the replacement of incompatible fuel delivery materials and secondly, the improvement of biodiesel oxidation stability [18–21]. Replacement of existing materials to suit the characteristics of biodiesel is deemed impractical since fossil diesel is still the primary fuel used in diesel engines. Furthermore, the recommended replacement materials such as stainless steel, aluminium (Al) and fluoroelastomers are more expensive than the existing copper and nitrile rubber used. As such, the majority of the studies in this subject area are focussed on improving biodiesel oxidation stability. Natural antioxidants are originally contained in the biodiesel feedstock however they are usually degraded during the refinement and purification process of biodiesel production. Hence, antioxidants such as butylated hydroxytoluene (BHT) are routinely added to further improve biodiesel oxidation stability [22,23]. The major drawback to this approach is the need for exact quantification of the antioxidant concentration. For example, a lower concentration than required might delay the oxidation process, but not completely inhibit it [24]. Conversely, a higher concentration than necessary could cause the antioxidant to act as pro-oxidant which accelerates the oxidation process instead [24].

Although extensive studies have reported on the adverse effects of oxidized biodiesel on fuel delivery materials, limited studies have been conducted to ascertain the deterioration process of biodiesel during actual diesel engine operation. For instance, one such study by Wadumesthrige et al. [17] examined the deterioration of 20 vol% biodiesel blended with 80 vol% of diesel in a Titan Energy Sentry 5000 Mobile Utility generator set utilizing an inline five cylinder John Deere's 5030TF270 model unit pump diesel engine. The test was conducted at a steady load of 30 kW. The analytical tests carried out included oxidation stability, viscosity, cold flow properties, derived cetane number, dissolved metals concentration, heat of combustion, and fatty acid composition. The difference between this study and the present work is that biodiesel blends were tested instead of neat biodiesel. Meanwhile, other studies have also investigated the deterioration of biodiesel under laboratory tests or test rigs which simulate engine conditions instead of an actual engine setup [11,16]. For this reason, experimental investigations were carried out here to determine the deterioration of neat palm biodiesel under the common rail diesel engine (CRDE) operation. The objectives of the study were to assess the oxidation conditions of biodiesel and to establish the presence of fuel delivery materials promoting factors such as the total acid number (TAN) and the water content under CRDE operation.

2. Material and methods

The experimental methodology can be divided into two stages. In the first stage, the deterioration of palm biodiesel with 10.5 h of oxidation stability according to the Rancimat test under CRDE operation was determined using an engine test-bed set up with a Toyota 1KD-FTV engine coupled to an SAJ Group SE-250 dynamometer. The World Harmonized Stationary Cycle (WHSC) and the Coordinating European Council Direct Injection Common Rail Diesel Engine Nozzle Coking Test (CEC F-98-08) speed-load test cycles were employed to simulate typical and severe driving conditions, respectively. Analytical tests to determine the oxidation condition of biodiesel under CRDE operation were subsequently carried out on biodiesel samples collected from the bottom of the storage prior to the tests as well as at every 32 and 30 min intervals for WHSC and CEC F-98-08, respectively. The analytical tests included oxidation stability, Fourier transform infrared spectroscopy (FTIR), peroxide value, fatty acid composition, dissolved metals, dissolved oxygen, viscosity, hydrogen ion concentration and conductivity value. Additionally, TAN and water content analyses were also conducted to assess the influence of engine operation on these. Sections 2.1–2.4 detail the associated materials and methods for the first stage.

The second stage was carried out following the results of the first stage which indicated that the deterioration level of biodiesel under engine operation could be gauged using the biodiesel conductivity value. As such, tests were conducted to ascertain the influence of fuel temperature, dissolved metals, oxidized biodiesel and biodiesel heating duration on the biodiesel conductivity value. Section 2.5 describes the procedures for the second stage.

2.1. Experimental set-up of the engine test-bed facility

The engine test-bed used consists of a Toyota 1KD-FTV engine which is coupled to an SAJ Group SE-250 model dynamometer (Supplementary Table 2 and Fig. 2). The engine is a 3.0 L, 4-cylinder inline CRDE with a turbocharger and intercooler while the dynamometer is a 150 kW eddy current dynamometer. The fuel lines and fuel tank were replaced with original equipment manufacturer components while the fuel pump and fuel injectors were cleaned prior to the investigation. The engine was determined to be capable of producing 90% of its rated power using B100. The engine utilizes Toyota D-4D CR fuel injection technology for operation at an ultra-high pressure of up to 1350 bar. This is combined with a 32-bit engine control unit which governs the fuel quantity, valve-timing and boost pressure at different engine parameters.

A cooling system was installed for the turbocharger intercooler system to increase the intake charge density and obtain maximum power output. This was achieved by maximizing the heat rejection of the compressed air from the turbocharger at the intercooler. This system was designed to draw in external air through a duct to blow at the intercooler using a Toyo 2.2 kW blower. A heat exchanger with a capacity of 12 L was installed in place of the radiator to improve the engine's cooling system. Another heat exchanger was also installed to further improve heat rejection from the engine oil. The additions of both the heat exchangers coupled with cooling towers were crucial to facilitate high speed-load engine operations at the specified durations.

Data was monitored and recorded using a DSG DaTAQ PRO data-acquisition system. The input and output data for the fuel flow rate and fuel temperature were recorded using a flow meter and K-Type thermocouples, respectively. The DaTAQ PRO has a refresh rate of 5 s and 100 points were averaged. Among the data of interest were engine speed, engine load, engine power, fuel temperatures (supply and return) and the fuel flow rate for determining fuel consumption.

2.2. Test fuel

Palm biodiesel without additional antioxidants from Vance Bioenergy, Singapore with 10.5 h of oxidation stability according to the Rancimat test was used. Its specifications are listed in Supplementary Table 3. To eliminate batch to batch variations, the same batch of fuel was used for all the tests. 76 L of fuel was fixed for all the experiments to match the typical fuel storage of the Toyota Hilux sold in Malaysia, which is equipped with the same 3.0 L 1KD-FTV CRDE. Minimum levels of 3.0 and 2.4 L of fuel were required to sustain engine operation and subsequent analytical tests, respectively. As such, operating the engine under the