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Combustion performance and emission analysis of diesel engine fuelled with water-in-diesel emulsion fuel made from low-grade diesel fuel

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ABSTRACT

In the present research, an experiment is designed and conducted to investigate the effect of W/D originating from low-grade diesel fuel (D2) on the combustion performance and emission characteristics of a direct injection diesel engine under varying engine loads (25–100%) and constant engine speed (3000 rpm). Four types of W/D are tested, which consist of different water percentages (5%, 10%, 15% and 20%), with constant 2% of surfactant and labelled as E5, E10, E15 and E20, respectively. The specific fuel consumption (SFC) of the engine when using each type of W/D is found to be reduced overall. This is observed when the total amount of diesel fuel in the emulsion is compared with that of neat D2. E20 shows a comparable maximum in-cylinder pressure and pressure rise rate (PRR) compared to D2 in all load conditions. In addition, it produces the highest maximum rate of heat release (MHRR) in almost every load compared to D2 and other W/Ds. NOx and PM are found to be reduced for all types of W/D. The carbon monoxide (CO) and carbon dioxide (CO_2) emissions increase compared to D2 at low load and high load, respectively. Overall, it is observed that the formation of W/D from low-grade diesel is an appropriate alternative fuel method that can bring about greener exhaust emissions and fuel savings without deteriorating engine performance.

1. Introduction

Fossil fuel combustion is the largest contributor to climate change representing 57% of the total greenhouse gasses [1] and it is largely produced from industrial and transportation emissions. Due to the severe environmental issues that the world is facing, starting from the Kyoto Protocol, which was established in 1997, new emission regulations are constantly being introduced. The regulations continue to be revised and enacted until present when the emission standards are generally stricter, especially in developed countries. The vehicle emission standard (Euro standard) is an example of an emission standard constructed specifically for vehicles and it is categorised based on the formation of nitrogen oxides (NOx), hydrocarbon (HC), particulate matter (PM) and the carbon monoxide (CO) in vehicle exhaust emissions. Fuel quality is also required alongside the Euro stages; in order to meet air quality requirements, the significant reduction in sulphur limits and complete ban on lead was necessary for vehicles meeting Euro 3 and above, together with other parameters, such as benzene and olefins or aromatics, which need to be significantly reduced [2]. Low-grade fuel (Euro 2 and below) is widely used in not only the non-developing countries but also in some developing nations [3]. The aforementioned fuel contains very high sulphur as well as other variables, such as lead, benzene and olefins or aromatics, all of which may be the basis of severe damage to the environment and also to the engine. Studies have reported that the sulphur content in fuel has a major influence on the formation of PM emissions. In normal heavy fuel, approximately 35% of total PM is produced from the sulphates [4].

Water-in-diesel emulsion fuel (W/D) is a promising alternative fuel that can reduce harmful exhaust emissions, especially NOx and PM emissions, while simultaneously improving the combustion efficiency [5]. Another encouraging feature in W/D is the usage of the aforementioned fuel that does not require any modification to the engine [6]. There is a special occurrence in W/D ignition called the micro-explosion phenomena that intrigues researchers worldwide, as it is non-existent in other normal diesel combustion. It is a secondary atomization of the primary spray as a result of the

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rapid evaporation process of water that is initially contained in the oil drop, making the combustion more efficient [7]. Numerous studies have been conducted concerning the W/D emulsion fuel involving the performance and emissions of an engine running on the said fuel, in return, explaining the combustion characteristics and micro-explosion process. According to Abu-Zaid [8] brake thermal efficiency is increased by 3.5% from that of the neat diesel fuel. Basha et al. [5] found that the measurement increased to 26.9% compared to diesel, which is 25.2%. Other study also agrees with these positive findings of using W/D [9]. As for brake power and torque, contradictory results have been reported. Alahmer [10] found that these two measurements are increased when the engine is powered with the 5% water-emulsified fuel. This is in agreement with the results reported by Abu Zaid [8] where the brake power and torque is amplified when the percentage of water is increased up to 20% by volume. However, a contradictory result is found by Yang et al. [11], where the brake power and torque are slightly reduced when using the W/D. Similar finding is reported by Selim [12], where he concluded that adding water to the diesel fuel caused the brake power output to drop slightly. Brake specific fuel consumption has been reported to increase after engine testing with W/D emulsion fuel [13], whereas Tsukahara and Yoshimoto [14] found it to reduce when water content and particle size in W/D is increased. It is however noted that the majority of studies show a remarkable reduction in NOx and PM when W/D is utilised. Attia and Kulchitskiy [15] found that NOx is reduced to 25% when large size of water droplets is used in the emulsion. Others reported that NOx is decreased by 30% after using 25% of water in emulsion fuel [4]. Ochoterena et al. [16], reported that the PM emission is reduced to 81% and 89% by using the W/D emulsion fuel and micro-emulsion fuel respectively. In respect of CO and HC readings, Subramaniam reported that these values were amplified [17], while some researchers found that they slightly decreased [15] and others revealed no difference compared to diesel fuel [11].

From the brief summary of the experimental results reported, it shows inconsistent findings in respect of the performance and exhaust emission studies. Many parameters are involved when utilising the aforementioned fuel that may influence the findings. Nicholas et al. [18] investigated the effect of the dispersed droplet size in emulsion with the strength of micro-explosion. They tested different mean water particle sizes of W/D emulsion ranging from 2.1 μm to 4.5 μm in the flat flame burner. The results show that the 4.5 μm water particle shows the most intense explosion. In support of that, Mura et al. [19] reported that from their experimental findings, the optimum dispersed water droplet size is 4.7 μm. After this point, the strength of the explosion begins to fall; from their observation, the larger droplet size (17.4 μm) showed a less intense explosion compared to 4.7 μm. Furthermore, Jeong and Lee [20] conducted an experiment to see the effect of different water percentages on the micro-explosion behaviour. The authors observed that when the water content in the emulsion is higher, the intensity of the micro-explosion seems to become vigorous and the duration of the explosion is elongated. The engine operating conditions during the testing may also affect the outcomes. According to Sheng et al. [21], they found that a 3–5% improvement in engine performance can be achieved by adjusting the injection timing to be advanced to two degrees of the crank angle when using the W/D fuel. Ithnin et al. [22] summarized the factors that influence the effectiveness of utilising the W/D in the engine based on the previous emulsion fuel studies; including size of the dispersed water particle, water content in the emulsion, ambient temperature, ambient pressure, type and percentage of surfactant, type of diesel engine and engine operating conditions.

Other than these parameters, the fuel quality in W/D emulsion fuel studies has received less attention, especially in utilising low-grade diesel as the emulsified fuel. Low-grade diesel fuel may cause more severe damage to the environment compared to higher Euro standard fuel. Hence, the idea to form the fuel into W/D is a good prospect to reduce these harmful emissions, and, at the same time, maintain/improve the engine performance. From this motivation, in the present experimental framework, a detailed analysis of engine performance and emission characteristics were conducted using four different water percentages of W/D (5%, 10%, 15% and 20%) formed from low-grade diesel, which is of Euro II quality (D2). The results are used for a comparison with neat diesel D2. A single cylinder, direct injection diesel engine is tested under four different load conditions (1 kW (25%), 2 kW (50%), 3 kW (74%), 4 kW (100%)) and with a constant engine speed of 3000 rpm. In the engine performance analysis, the peak combustion pressure, peak rate of heat release, maximum pressure rise rate and specific fuel consumption is discussed in detail. In respect of the emission characteristics, NOx, PM, CO and CO_2 are analysed before being further discussed.

2. Description of experimental setup

2.1. Engine testing setup

The schematic diagram of the engine testing setup is shown in Fig. 1. The type of engine used in the experiment is a 0.406 L single cylinder, four stroke, air-cooled, direct injection diesel engine. The combustion system of the engine is toroidal crown and the intake port type is helical. The other basic specifications of the engine are shown in Table 1. The engine is coupled to an AC alternator for loading together with other instrumentation devices for measuring the engine performance as well as the exhaust emissions. The instrumentation for measuring engine performance consists of the following devices; (i) a fibre optic pressure transducer which is installed in the cylinder head for measuring the instantaneous in-cylinder combustion pressure inside the combustion chamber and (ii) the crank angle encoder, which records the crank angle of the rotating crank shaft. The data from both sensors are transmitted to a sensor interface for the synchronization process and analysis by TFX Engine Technology data acquisition system in order to get the combustion pressure versus crank angle plot. For each test, a continuous 50-cycle combustion pressure is recorded and reported after averaging them.

As for the measurement of emissions, a Testo 350 emission analyser is used to measure the NOx, CO and CO_2 contents in the exhaust gas emitted by the engine. The specification of the Testo 350 emission analyser is shown in Table 2. The measurement is recorded for every 5-s interval during the 2 min duration of engine running and the average data are calculated for consideration and discussion. The PM reading is taken using the mini-dilution tunnel where 10% of exhaust gasses are diluted by clean air inside the tunnel with a controlled temperature of 50 °C. The diluted gas is then absorbed by the uniform velocity of the diaphragm pump in which the particulate is then trapped on a Teflon filter (MILLIPORE FHLP04700, diameter 47 mm, orifice 0.45 μm). The particulate concentration is determined by measuring the filter weight before and after sampling. The engine tests are performed for different engine load conditions consisting of 1 kW (25%), 2 kW (50%), 3 kW (74%) and 4 kW (100%), with a constant engine speed of 3000 rpm. The engine is initially run for 10–12 min and the corresponding exhaust temperature and speed are monitored. Once these parameters became steady, data are recorded.

2.2. Water-in-diesel emulsion fuel (W/D)

The presence of a surfactant, sometimes called an emulsifier, is crucial in forming a stable W/D emulsion. The surfactant works as