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Experimental Investigation on a Diesel Engine Fueled by Diesel-Biodiesel Blends and their Emulsions at Various Engine Operating Conditions

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HIGHLIGHTS

- Fuel property comparison between conventional diesel and emulsion of diesel-biodiesel blends up to B40 is done.
- The chemical characteristics of emulsions of diesel-biodiesel blends are investigated.
- The emulsion fuel effect on diesel engine emission and performance is studied.
- Reduction in NOx and smoke with emulsion fuels is concluded.

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ABSTRACT

The present work aims to investigate emulsion fuel characteristics with different levels of water concentration and their effects on performance and emissions of a light-duty diesel engine. The engine was operated at three engine speeds of 1000, 2100 and 3000 rpm, respectively. At each speed, three loads (20%, 50%, and 80%) were applied. Diesel and biodiesel-diesel blends up to 40 by step of 10 were emulsified with three different levels of water concentration (5%, 10% and 15%). Emulsifiers Sorbitan Monoleate (Span 80) and Polyoxyethylene Sorbitan Monoleate (Tween 80) were used to prepare emulsion fuels. Fuel properties, stability and particle size distribution were measured. Engine performance (brake-specific fuel consumption (BSFC) and brake thermal efficiency (BTE)) and emissions were investigated. An increase in BTE was observed with increased water content in emulsions. A reduction in exhaust gas temperature (EGT) with an increase in water content was achieved. The nitrogen oxides (NOx) and smoke emissions were also significantly reduced with the increase in water content in the emulsion compared to their bases. Emulsion fuel containing a higher water content revealed a considerable increase in carbon monoxide (CO) emissions.

1. Introduction

Diesel engines are widely used in many applications, such as transportation, mining equipment, and agriculture machinery due to their high-energy conversion and economic power source [1]. However, diesel engines contribute to environmental pollution, with hydrocarbon (HC), CO, NOx and particulate matter (PM) as the main pollutants from the combustion process [2–4]. Increased concerns over environmental issues and conventional resource depletion have heightened the motivation to use clean and alternative fuels. Biodiesel is a prospective clean diesel engine fuel, and is defined as the mono alkyl esters of long-chain fatty acids derived from renewable lipid feedstocks, such as vegetable oil and animal fats [5,6]. Biodiesel has a lower heating value, but has a higher cetane number and oxygen content than fossil diesel [7–9]. In terms of engine emissions, biodiesel emits lower HC, CO and PM, whereas NOx emission is higher compared to that of conventional diesel [10–12]. The higher NOx formation is due to the elevated oxygen content in biodiesel, as well as high combustion temperatures [13–15]. Attempts have been made to reduce the combustion temperature. For example, the introduction of water into the combustion chamber, whether through direct injection as a steam-into-intake air system or as fuel emulsion of a diesel engine is an effective technique to increase thermal efficiency and reduce combustion temperature and engine emissions [16–18].

Emulsion fuel is a blend of fuel (nonpolar liquid) and water (polar liquid) with emulsifiers [19,20], which usually consists of two surfactants that can reduce the surface tension between

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Nomenclature

BSFC	brake specific fuel consumption
BTE	brake thermal efficiency
Cc	cubic centimeter
CO	carbon monoxide
CO_2	carbon dioxide
cSt	centistoke
°C	degree celsius
EB	emulsified biodiesel
EGT	exhaust gas temperature
g/kW h	gram per kilowatt-hour
g/L	gram per liter
HC	hydrocarbon
HLB	hydrophile-lipophile balance
kg/m^3	kilogram per cubic meter
kJ/kg	kilojoule per kilogram
kW	kilowatt
mg/m^3	milligram per cubic meter
ml/min	milliliter per minute
mm	millimeter
µm	micrometer
NO	nitric oxide
NO_2	nitrogen dioxide
NOx	oxides of nitrogen
O_2	oxygen
O/W	oil-in-water
O/W/O	oil-in-water-in-oil
PM	particulate matter
Ppm	parts per million
Rpm	revolution per minute
Span 80	sorbitan monoleate
Tween 80	polyoxyethylene sorbitan monoleate
W/O	water-in-oil
W/O/W	water-in-oil-in-water

immiscible liquids [21]. Polar liquid is liquid with a slightly different charge at the ends of each molecule; those molecules can dissolve only in a polar solvent. Nonpolar liquids have an equal charge at each end of their molecules, which dissolve only in a nonpolar agent. Surfactants are usually substances containing an unequal concentration of polar and nonpolar molecules. The surfactant that has affinity to polar liquid is called hydrophilic, whereas the surfactant with more affinity to a nonpolar liquid is referred to as lipophilic. Each surfactant has a numerical value called hydrophilic-lipophilic balance (HLB), ranging from 0 to 20 [22]. The HLB is a weight percentage indication of the hydrophilic portion in a surfactant. The surfactant is called lipophilic when it has an HLB value lower than 9, while it is named hydrophilic when its HLB value is higher than 11 [23]. The emulsion is comprised mainly of a two-phase emulsion: water-in-oil (W/O), or oil-in-water (O/W) [24], and of a three-phase emulsion: water-in-oil-in-water (W/O/W), or oil-in-water-in-oil (O/W/O) [25]. Lin and Chen [26] concluded that two-phase emulsion has advantages of lower mean droplet size and higher heating value compared to three-phase emulsion. Generally, the emulsion fuel could be prepared using different approaches: ultrasonic emulsion [27], conductive emulsion [28], or external force [29]. Lin and Chen [26] used an ultrasonic vibrator and a homogenizer mixer for preparing diesel emulsion, and indicated that using a vibrator resulted in better stability of emulsion over seven days, with a lower mean particle size of the water.

Water quantity and the concentration of surfactants in the emulsion, as well as the suitable value of HLB, play a major role in the emulsion's stability. Raheman and Sweeti [30], using a homogenizer mixer at a speed of 2500 rpm, prepared three emulsion fuels with three different HLB values, water quantity and surfactant concentrations. They observed that 10% water produced better results with 0.5% and 1% surfactant at 5 HLB. Melo-Espinosa et al. [31], and Noor El-Din et al. [32] reported that increasing the emulsifier concentration up to 10% in total volume with low water content resulted in increased emulsified fuel stability and decreased the emulsion's droplet size. Debnath et al. [22] conducted a comprehensive review of fuel emulsion, wherein they mentioned that a three-phase emulsion using Span 80 as an emulsifier provides better stabilization compared to Tween 80 at the same concentration. According to Leng et al. [33], increasing the emulsifier concentration up to 30 (g/L) and decreasing the water content in the emulsion fuel improved the emulsion stability over 90 days.

The viscosity and heating value of an emulsion fuel are two indicators affected by water content of the emulsified fuel. Generally, fuel with higher viscosity than diesel fuel resulted in a decrease in the injection rate, power, fuel atomization, and vaporization by the injectors; consequently, an incomplete combustion occurred, which resulted in soot emission [34,35]. Ithnin et al. [36] prepared diesel emulsion with four different levels of water content using Span 80 and Tween 80 as surfactants; they observed an increase in diesel emulsion viscosity with an increase in the emulsion's water. Similarly, a study conducted by Zhang et al. [37] concluded that viscosity rises by increasing water content in an emulsified fuel. Qi et al. [38] reported that increasing water quantity in the emulsion fuel reduces the heating value of the emulsified fuel and increases the ignition delay of diesel engines. Hsieh et al. [39] focused their study on finding a combination between HLB of emulsifiers and gross heating value. The relationship was found to be linear, and the highest HLB value indicated the lowest gross heating value.

Emulsion fuel has positive effects on diesel engines in terms of engine performance and emissions. The experiment conducted by Senthil et al. [40] investigated diesel engine emissions and performance, using a fuel with an emulsion blend of 20% biodiesel and diesel, with various percentages of water content. Their investigation concluded that the emulsion fuel resulted in slightly lower BTE. HC, NOx and smoke opacity were also lower compared to that obtained from B20 and diesel. Scarpete [41] studied emission reduction of a diesel engine fueled by emulsified diesel, and found a significant reduction in NOx and PM emission when the diesel engine ran on emulsion fuel. Using 1% Span 80 with two different water content levels, Hasannuddin et al. [42] prepared emulsified diesel to investigate diesel engine emissions, and observed that the NOx and PM emissions were reduced, while the CO emission increased compared to diesel at a low load. Yang et al. [43] tested diesel engine performance fueled with emulsion fuel with nano-organic additives, during which they obtained higher BTE compared to neat diesel. Ogunkoya et al. [44] operated a diesel engine with three different types of emulsion fuel to analyze engine performance. They observed that using three types of emulsion fuel resulted in a reduction of output and mechanical efficiency, with a slight increase in BTE and BSFC compared to their base fuels. Baskar and Senthil Kumar [45] conducted an investigation on diesel engine performance fueled with emulsified diesel while supplying oxygen into the intake air system, and they reported