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Research Paper

Combustion, performance and exhaust emission characterizations of a diesel engine operating with a ternary blend (alcohol-biodiesel-diesel fuel)

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HIGHLIGHTS

- Comprehensive comparison of combustion, performance and emission characteristics of ternary fuel blends.
- Higher CP_{max}, HRR_{max} and R_{max} values of alcohol blends.
- Very close BTE values to each other for all fuels used in the experiments.
- Significant reduction in smoke emissions with the addition of alcohols.

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ABSTRACT

Interest in alternative and clean energy has increased in order to meet increasing energy need and control over air pollution. In this context, studies on renewable alternative fuels such as biodiesel and alcohols for diesel engines continue intensively. However, pure biodiesel cannot be used alone in diesel engines due to its high density and viscosity. Therefore, in order to improve the density and viscosity of the biodiesel blend, alcohols are used as a fuel additive. The objective of this study is to evaluate the effect of the biodiesel and various alcohols additions to petroleum-based diesel fuel (DF) on combustion, performance and emissions of a single-cylinder diesel engine at different engine loads. In preparing the fuel blends used in the experiments, 20% cottonseed biodiesel was first mixed with DF and coded as B20. The mixture ratio was set at 20% biodiesel: 10% butanol, 10% ethanol, or 10% methanol and coded as B20Bu10, B20E10, and B20M10, respectively.

Our results showed that ignition delay (ID) of the biodiesel and alcohol blends was longer than that of DF because of their low cetane numbers. The values of maximum cylinder pressure (CP_{max}), maximum pressure rise (R_{max}), and maximum heat release rate (HRR_{max}) of B20 and their locations were very close to the DF at all the loads. However, due to the low cetane number of the alcohols and the rapid combustion of the fuel accumulated in the combustion chamber during the long ignition delay, the CP_{max}, HRR_{max} and R_{max} values of the alcohol blends were higher than those of B20 and DF for all the engine loads. This difference was more apparent at the high engine loads. Since the heating values of the biodiesel and alcohols were lower than those of DF, the B20 and alcohol blends had higher brake specific fuel consumption (BSFC) values. The brake thermal efficiency (BTE) values of all the fuels used in the experiments were very close to each other, followed a similar trend and reached their maximum at 0.27 MPa. The B20 and alcohol blends led to a slight increase in nitrogen oxide (NO_x) and hydrocarbons (HC) emissions while reducing smoke and carbon monoxide (CO) emissions. With the addition of the alcohols, a significant reduction in smoke emissions was observed at all the engine loads due to the high oxygen content and low C/H of the alcohols.

1. Introduction

Recently, the interest in alternative fuels has increased due to the decrease in oil reserves and the rise in oil prices and environmental concerns. Biofuels such as biodiesel and alcohols from renewable sources are attractive alternative solutions to meet increased energy demands and to reduce exhaust emissions [1]. Diesel engines are widely used because of their high power output and high fuel efficiency. They also exhibit lower emissions of conventional exhaust pollutants such as CO and unburned HC than do gasoline engines [2].

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There are various types of alternative fuels, but biodiesel is considered to be the most promising, clean and alternative fuel for diesel engines. Biodiesel can be produced from vegetable oils or animal fat feedstocks by alcohol transesterification and does not contain aromatics and sulfur [3]. In addition, it contains about 10–15% oxygen by weight [4]. Biodiesel is a renewable, biodegradable, non-toxic fuel and has similar combustion characteristics to diesel fuel. For this reason, it can be used directly or by blending with diesel fuels in compression ignition engine [5]. Biodiesel has also some negative fuel characteristics such as low volatility, high density, high viscosity, and high pour point [6]. For these reasons, pure biodiesel is not widely used in diesel engines without any modification. The physical properties of the fuel are very important parameters in the diesel engines during the atomization process. For example, viscosity of biodiesel is very effective in the distribution of the fuel droplet size, the atomization quality of the fuel injection, and the uniformity of the mixture [7]. One of the methods of reducing the density and viscosity of biodiesel is the addition of alcohol which improves the overall fuel properties of the fuel blend [8]. In addition, alcohols have been reported to be a suitable additive for diesel and biodiesel fuel in order to reduce exhaust emissions and improve engine combustion because of the high oxygen content [7].

The cetane number is one of the most important parameters indicating fuel ignition quality and determining the duration of ID. The increase in the cetane number is directly proportional to the length of the carbon chain. Typical diesel engines require a cetane number between 45 and 60, and when the cetane number drops below 38, the ID increases rapidly. In general, alcohols have a lower cetane number (8 for ethanol, 3 for methanol and 25 for butanol) than diesel fuel, resulting in longer ID. Although the use of oxygen-rich alcohols improves both premixed and diffusion combustion stages, their lower heating values and cetane numbers, miscibility and stability problems, poor auto-ignition qualities, and inappropriate lubrication features limit the use of alcohols as a pure diesel engine fuel [9]. There are many studies in the literature to examine engine performance and exhaust emissions using alcohol fuels (ethanol, methanol, and butanol) blended with standard diesel fuels [10–16]. These studies have shown that alcohol fuel blends improve some exhaust emissions (CO and smoke density), but reduce diesel engine output torque and increase the BSFC [10].

Ethanol is most commonly used one in fuel studies among alcohols, as it is renewable and has more miscibility with diesel fuel. Ethanol improves the combustion and reduces the exhaust emissions such as CO and smoke due to its high oxygen content [17]. However, since the flash point of ethanol is much lower than diesel fuels, the preparation of fuel mixtures requires more precautions. Less studies exist in the literature about the use of methanol as an alternative diesel fuel additive than about that of ethanol [14,18,19]. Methanol can be obtained at a low cost from coal or petroleum-based fuels, but its miscibility in diesel fuel is rather limited. However, ethanol is a renewable fuel that can be produced from biomass such as corn, sugar beets, sugar cane, sweet sorghum, barley, cassava, and molasses by alcoholic fermentation of sugar. Ethanol can be also produced from agricultural residues such as raw materials, waste woods, and straw [20]. Compared to ethanol and methanol, butanol has very similar fuel properties to diesel fuels. Butanol has some advantages as an alternative fuel additive for compression ignition engines due to its higher cetane number, higher miscibility, and lower vapor pressure. In addition, butanol has less corrosivity and higher energy content and is a biomass-drived renewable fuel such as ethanol.

The use of alcohols as a diesel fuel additive has some limitations due to the low cetane number, low miscibility and long ignition delay. Although biodiesel appears to be the smartest choice among biofuels, there are also some challenges in using biodiesel as a fuel in the diesel engine [8]. For this reason, the use of ternary fuel blends in the diesel engines is considered a solution to reduce the above-mentioned drawbacks of biodiesel and alcohol. There are many studies in the literature on the effects of ternary fuel blends (diesel, biodiesel, and alcohol) on the diesel engine combustion and performance as well as pollutant emissions such as smoke, NO_x, CO, and HC. The influences of various alcohol-biodiesel-diesel blends on the combustion, performance, and exhaust emissions of the diesel engines are discussed below.

Guido et al. [21] studied the effect of bioethanol addition to rapeseed methyl ester-diesel blend in a four-cylinder light-duty diesel engine. Test results showed that ethanol addition significantly reduced smoke and NO_x emissions but increased CO and HC emissions and BSFC. Bhale et al. [22] examined the effect of ethanol addition to mahua biodiesel on engine performance and exhaust emissions. They reported that the ethanol blend reduced CO and NO_x emissions but increased HC emissions. Zhu et al. [23] investigated the effects of ethanol-biodiesel blends on the combustion, performance and emission characteristics of a four-cylinder direct-injection diesel engine. Their results showed that the ethanol-biodiesel blends caused higher BTE and lower particulate matter and NO_x emissions than the diesel fuel. In addition, with increased ethanol concentration in fuel blends, CO and HC emissions and BSFC increased. Yasin et al. [7] examined the effect of the ternary fuel blend (methanol-biodiesel-mineral diesel) on the performance and emissions of the diesel engine. They noted that the ternary fuel blend reduced CO emissions but increased NO_x emissions and BSFC. Kumar et al. [24,25] tested the methanol-jatropha oil blend in a diesel engine and stated that NO_x emission decreased, whereas HC and CO emissions increased at low loads and decreased at high loads. The butanol-biodiesel blend with 20% butanol was reported to lead to higher CO and HC emissions and lower NO_x emissions than diesel fuel [26]. Despite a slight increase in NO_x emissions and BSFC, a significant reduction in smoke emission was observed. In addition, the effects of butanol on the combustion process were investigated. Tosun et al. [27] analyzed the effects of the addition of 20% ethanol and methanol to peanut methyl ester on the fuel properties, performance, and emissions. They reported that butanol-biodiesel blend had higher engine power and torque than diesel fuel.

Wang et al. [28] studied change in the exhaust emissions of the diesel engine using an ultralow-sulfur diesel fuel blended with ethanol, biodiesel and dimethyl ether. Their main results showed that the particulate matter (PM) emission decreased with the increased oxygenate content of the blends. Ethanol addition to diesel fuel increased HC, CO, NO_x and NO_2 emissions and decreased particle number concentration. Huang et al. [29] investigated the combustion characteristics of a compression-ignition engine operating on the stabilized diesel/methanol blends. Their study showed that increased methanol mass fraction of the diesel/methanol blends increased the heat release rate (HRR) in the premixed burning phase and shortened the combustion duration of the diffusive burning phase. The ignition delay increased with the fuel delivery advance angle for both diesel fuel and the diesel/methanol blends. For a specific fuel delivery advance angle, the ignition delay increased with the increased methanol mass fraction (oxygen mass fraction) in the fuel blends, with the obvious behaviors at a low engine load and/or a high engine speed. The rapid burn and total combustion durations increased with the fuel delivery advance angle. Ren et al. [30] investigated the combustion and emissions of a direct injection diesel engine fuelled with six selected oxygenated fuel blends. They found that the ignition delay decreased with the increased diglyme fraction of the blends due to high cetane number of the diglyme. However, the ignition delay of the other diesel oxygenate blends increased with the increased oxygenate fuel fraction of the fuel blends due to the low cetane numbers of the oxygenate fuels. Combustion durations decreased with the increased oxygenate fraction of the blends. In addition, they reported that the reduction of smoke was strongly related to the oxygen-content of blends, and CO and HC concentrations decreased with the increased oxygen mass fraction of the blends.

As mentioned above, a number of studies have been conducted on diesel engines to examine the exhaust emissions and engine performance of various alcohol-biodiesel diesel blends. However, studies on

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