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Research Paper

Experimental analysis on the performance and emissions of diesel/butanol/biodiesel blended fuels in a flame tube boiler

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HIGHLIGHTS

- Butanol/biodiesel blended fuels decreased the size of the peak temperature zones.
- CO emissions decreased significantly from 281 ppm to 4.5 ppm by using D70B30.
- NO_x emissions did not change considerably, remained by about 46–48 ppm.
- Efficiencies increased from 90.5% to 90.8% by using D70B30 fuel.

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ABSTRACT

This paper presents an experimental study of combustion of diesel/butanol/biodiesel blended fuels and their effect on boiler performance and emissions in a reversal flame tube boiler. Pure diesel, blends of diesel/butanol, and blends of diesel/butanol/biodiesel were used in the experiments. Before the combustion experiments, the miscibility of different fuel types was examined. To investigate the characteristics of combustion by using different fuel blends, the temperature distributions in the combustion chamber and smoke tube were determined. Exhaust gas temperature and exhaust gas emissions were measured in the boiler exit. The results showed that by using diesel/butanol blends the size of the peak temperature zones in the combustion chamber decreased gradually from D100 to D70B30. As a consequence of better combustion conditions in the combustion chamber, CO emissions decreased gradually from 281 ppm to very low values of 4.5 ppm, exhaust temperature decreased nearly 13 °C and efficiency increased nearly 0.3%, from D100 to D70B30. In triple mixtures, as the amount of biodiesel in the mixture increases, the maximum temperature in the boiler also increased compared to D70B30 and the amount of CO also increased. Also, NO_x emissions did not change significantly in all experiments and remained by about 46–48 ppm.

1. Introduction

The demand for energy, which is the main source of social and economic development, has been increasing day by day. The world's energy resources have been limited, so countries have turned their energy policies back on and planned to use energy efficiently. The availability of sustainable and reliable energy source is essential to economic growth for developing and developed nations. Increasing use of consumable resources, negative effects on the environment and the dependency from the import of fossil have led researchers to alternative and renewable energy sources. Biologically based fuels (biodiesel and bioalcohols) proved themselves as alternatives to petroleum fuels.

Alcohols are generally classified by the formula $C_nH_{2n+2}O$. They are colorless and have a sharp odor. Alcohols have a smaller molecular structure than petroleum fuels, contain oxygen in their structure, and do not have sulfur or other impurities as in fossil fuels. As an alcohol ethanol is mostly used as an alternative fuel or fuel additives especially in gasoline engines and also in diesel engines. Butanol is far less used but has more advantages compared to ethanol. Ethanol's miscibility with diesel is poor but butanol can be easier mixed without phase separation [1]. Besides, butanol's lower heating value is higher than ethanol. Further butanol can be produced like ethanol by fermentation of biomass containing cellulose, that is especially not usable as food. Therefore biomass-based butanol can be seen as a renewable fuel and is called as biobutanol. Butanol has several isomeric structures i.e. *n*-butanol (*n*-C_4H_9OH), sec-butanol (sec-C_4H_9OH), iso-butanol (iso-C_4H_9OH) and tert-butanol (tert-C_4H_9OH) but biomass-based

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Nomenclature

A_{sto}	stoichiometric air fuel ratio (kg air/kg fuel)
c_p	specific heat (kJ/kg K)
LHV	lower heating value (kJ/kg)
$\dot{m}$	mass flow rate (kg/s)
Dx	x% volume of commercial diesel fuel of blend
Bx	x% volume of *n*-butanol of blend
BDx	x% volume of biodiesel of blend

Greek symbols

λ	excess air coefficient
η	thermal efficiency

Subscripts

fg	flue gas
exh	exhaust
amb	ambient

butanol has mostly straight chain molecules, *n*-butanol (normal butanol) [2].

Biodiesel is similar to petrodiesel and can be used purely or mixed with petrodiesel in every ratio. The major difference between biodiesel and petroleum derivatives is that biodiesel contains 10–11% oxygen on a mass basis in itself. Pure biodiesel and petrodiesel/biodiesel blends can be used at certain rates in diesel engines or burners, without any changes or with minor modifications. The production of biodiesel can be made from animal fats, vegetable oils and waste cooking oils with an alcohol in the presence of a catalyst. Biodiesel is generally made via a transesterification process, whose final product is a mixture of methyl or ethyl esters [3].

Boilers are closed vessels which produce heat energy from burning of fuels. Energy efficiency in boilers depends on the quality of the combustion and heat transferred from the combustion products to the working fluid.

Literature studies have been performed on the combustion of diesel and diesel/alcohol/biodiesel blended fuels. It has been observed that there are a lot of studies about biofuel mixtures in internal combustion engines. On contrary, there are only a small number of studies which have been carried out on boilers.

Zhang et al. [4] have experimentally examined the effect of butanol addition on performance and emissions in a low-temperature diesel engine. Experiments demonstrated that the butanol ratios in the modified single-cylinder diesel engine were 20% and 40% by volume, and the *n*-butanol addition resulted in a nearly zero emission of CO and total hydrocarbon emissions, even with the addition of 40% butanol. Marek et al. [5] investigated the use of ethanol blended diesel fuel in diesel engine. They monitored 30 buses, of which 15 buses were operated with a 15% ethanol-85% No.1 diesel mixture fuel and the other 15 buses were run with No.1 diesel fuel. They stated that no abnormalities and fuel-related problems were detected up to 434,500 km with the fuel blends. Similar work has been done by Hansen et al. [5] on John Deere and Caterpillar tractors and they have not encountered any problems. The result from this study is that there is no significant performance loss when diesel is blown up to 10% ethanol mixture and there is no negative effect on the motor in long-term durability. Şahin et al. [1] experimentally examined the effect of diesel/butanol mixtures on turbo-diesel engine combustion on engine performance and emissions. They prepared the blends with 2%, 4%, and 6% butanol addition to the diesel fuel and they carried out their experiments at different engine speeds and loads. It was seen that there is a significant reduction in the soot emissions. The diesel/butanol mixtures have a low effect on the internal pressure of the cylinder and heat transfer. Rakopoulos et al. [6] experimentally examined the effect of diesel/butanol mixtures on diesel engine performance and emissions. They used 8%, 16% and 24% butanol by volume in mixtures. They observed that there was a significant decrease in soot emissions, a slight decrease in CO and NO_x emissions, and an increase in HC emissions. Karabektaş et al. [7] investigated the effects of 5%, 10%, 15%, and 20% isobutanol addition to the diesel fuel on the engine performance and exhaust emissions. As the amount of isobutanol increased, the HC, CO and NO_x emissions decreased. Siwale et al. [8] studied the effect of *n*-butanol-diesel mixtures on combustion characteristics and exhaust emissions in a 4-cylinder automobile engine. As a result of the study, a considerable reduction in soot emissions was observed as the amount of *n*-butanol in the mixture increased.

Saez et al. [9] studied the combustion of liquid butane as an alternative fuel in a diesel fuel burner. Experiments were carried out at different pressures for diesel and liquid butane at 0.8, 0.9 and 1 bar for diesel; 1, 1.5 and 2 bar for liquid butane with different excess air values. During the experiments, flame geometry, temperature, and combustion products were examined. It was seen that the liquid butane flame was in the form of an elongated cone and had low radiation and light blue color at the starting point. The liquid butane flame temperature and NO_x concentration were lower than the diesel, and the temperature of the liquid butane flame spread better in the combustion chamber. Park et al. [10] studied the atomization characteristics of diesel, biodiesel and biodiesel/ethanol mixtures. At different pressures and injection times of these three different fuels, injection speeds, fuel droplet diameters, and flying distances were investigated. They found that the burning delay of biodiesel blended with ethanol was lower than that of diesel and biodiesel and the droplet size was lower than other fuels. Parag and Raghavan [11] studied the combustion rates of pure ethanol and ethanol-fuel mixtures in a porous sphere experimentally. Experiments were carried out in different sphere sizes, different air velocities, and fuel types. The mass combustion rate of the fuel was found to increase with sphere size and air velocity. When water was added to the ethanol, the burning speed and the flame brightness decreased. No significant change in the mass combustion rate was observed when the diesel was mixed with ethanol, but as the diesel ratio in the mixture increased, the conversion rate decreased and the flame brightness increased. In addition, as the air velocity increases, the vortex turns into flame and the flame length is shortened seriously. Barroso et al. [12] examined a burner for diesel fuel in detail with diesel, ethanol, and mixtures of these two fuels at different injection pressures and different nozzle types. Experiments showed that bioethanol did not cause any SO_2 emissions, reduce the NO_x emissions by 50%, but increased CO emissions. The reason for this is, according to the opinion of the authors, that the burner is designed for diesel, which means that some modifications to the burner have to be made to burn bioethanol. Asfar et al. [13] have experimentally examined the ethanol-diesel mixtures combustion in their work. They achieved significant improvements in increasing combustion quality and reducing pollutants but if the alcohol content in the mixture is 10% or less, they could not observe a remarkable effect. Prieto-Fernandez et al. [14] found that the use of methanol and ethanol was effective in reducing the solid particles and unburned hydrocarbons at the outlet. In addition, combustion processes of