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Research Paper

Combined effects of soybean biodiesel fuel addition and EGR application on the combustion and exhaust emissions in a diesel engine

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HIGHLIGHTS

- The combining effects of 20% soybean biodiesel and EGR rate were investigated.
- EGR application did not cause significant penalties on the engine performance.
- NO_x and smoke emissions were simultaneously improved.

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ABSTRACT

In this study, soybean biodiesel fuel was blended in 20 vol.% with diesel fuel and tested in a single-cylinder, DI, four-stroke diesel engine under four different engine loads (15, 11.25, 7.5 and 3.75 Nm) and 2200 rpm engine speed with different EGR rates (5, 10, 15%). The results showed that the maximum heat release rate and maximum in-cylinder pressure were mostly increased with the combined effects of biodiesel fuel addition and EGR application. Premixed combustion fractions were generally increased at all the engine loads with corresponding decrease in the diffusion combustion fractions. Combustion durations were generally stable while the center of the heat release rates shifted toward TDC. Reasonable increments on the BSFC and reductions on BTE as a maximum 6% and 3% occurred with 15% EGR, respectively. NO_x and smoke emissions were improved simultaneously up to 55% and 15% at the high engine load, respectively. THC emissions at the low and medium engine loads decreased while deteriorations were observed with more than 5% EGR at the high engine load. Although CO emissions showed insignificant changes, there were increments at the high engine load. However, CO_2 emissions were slightly higher for all the engine loads.

1. Introduction

Research in internal combustion engines is continuing to increase as a challenge to find environmentally, friendly, and economically sustainable alternative fuels as a replacement for petroleum based fuels. Biodiesel as an alternative fuel has been consolidated its place in these efforts and gained wide acceptance for diesel engines with significant advantages and benefits [1–3]. Its important properties such as cetane number, flash point, non-toxic, biodegradable and good inherent lubricity are quite similar or better than diesel fuel. Moreover, it is a unique alternative fuel which can ensure the requirements of health effects testing [4]. Biodiesel can be blended with diesel fuel in different ratios or directly used in existing diesel engines without any modifications. Also, most of the engine manufacturers and diesel fuel injection equipment manufacturers have been extended their warranty coverage for the usage of biodiesel fuel up to 20% (in vol.) blends. Regarding the exhaust emissions, biodiesel as a renewable fuel has a little impact on greenhouse effect due to recycling of CO_2 to photosynthesis. It has an improving potential with a minimal sooting tendency and burns more completely because of its oxygenated nature and absence or negligible aromatic and sulfur contents. Despite of these advantages, its proportionally lower volumetric energy capacity, higher kinematic viscosity, inferior cold-flow properties, lower oxidative stability and mostly higher NO_x emissions are important drawbacks to be overcome for widespread use.

Biodiesel fuels can be produced from a wide variety of various feedstocks. Some of them, especially soybean derived biodiesel fuels, have attracted attention due to its higher potential for a renewable source. Since soybean is more abundant in most of developed

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countries and oil derivation can be up to 20% by weight, its prices are generally more reasonable than the other feedstocks. Thus, soybean oil has become the main favorable feedstock and covers a wide range in biodiesel fuel production. Considering these points, there still seems to be a need for investigations on the soybean derived biodiesel fuels. In the literature, some valuable studies have been conducted in recent years using soybean biodiesel fuel and their blends with diesel fuel. Canakci [5] conducted an experimental study in direct injection (DI) diesel engine fueled with No. 1 diesel, No. 2 diesel, soybean biodiesel and its 20% blend with diesel fuel. It was reported that break specific fuel consumption (BSFC) results were found identical when compared with diesel fuel. Also there was a slight increase about 13.9% for a neat soybean biodiesel and 2.9% for 20% blend, respectively. Significant reductions were seen on smoke, CO and HC emissions while NO_x emissions increased by about 11.2%.

Özener et al. [6] investigated the effects of diesel and soybean based biodiesel fuel blends (B10, B20 and B50) on the combustion, performance and emissions. It was concluded that brake torque decreased and BSFC increased between 2% and 9% from B10 to B100 when compared with diesel fuel. Furthermore, CO and HC emissions were found to be 28% and 46% lower but it was observed that NO_x and CO_2 emissions increased up to 17.62% and 5.03% higher, respectively. Their combustion results showed that biodiesel addition to diesel fuel resulted in decrease of ignition delay (*ID*) and the premixed combustion peak.

In another different study, Qi et al. [7] tested the soybean biodiesel and diesel fuels in a DI diesel engine under different engine speeds at full load and under different load characteristics at 1500 rpm. Besides earlier start of combustion timing (*SOC*) for the biodiesel fuel, they reported that similar combustion stages were found for both fuels with different engine speeds. In addition, both fuels showed different combustion characteristics when the engine load changed due to different properties of biodiesel and diesel fuels. They also pointed out that the identical power output of the engine with increasing BSFC results was found for biodiesel fuel. Moreover, significant improvements on CO, HC, NO_x and smoke emissions were seen under different speed characteristic at full engine load. Al-Dawody and Bhatti [8] investigated the effects of diesel and the blends of diesel-soybean biodiesel on combustion, performance and emissions in a single-cylinder, DI diesel engine. It was found that soot emissions reduced by 48.23%, but BSFC increased by 14.65% compared to diesel fuel. NO_x emissions increased for all biodiesel fuels compared to diesel fuel.

Bueno et al. [9] conducted steady-state engine testing with soybean based biodiesel fuel blends up to 30 vol.% concentrations in a high speed turbocharged DI engine. In their study, fraction of fuel exergy exchanging through indicated work, destruction by irreversibilities and losses with heat and mass transfers in the combustion and expansion processes were determined in order to assess the engine efficiency. They concluded that balance between break thermal efficiency (BTE) and fuel exergy reduction caused by biodiesel blending was found that govern the BSFC results. Also in their results, best values on the BTE were found with 20% soybean biodiesel fuel blend while 10% biodiesel ratio provided best values on brake power and BSFC results.

Differences on chemical and physical characteristics between soybean based biodiesel fuel and diesel fuel are also expected to bring about changes in the combustion and emission characteristics with regard to fuel spray and atomization characteristics. Park et al. [10] made detailed experimental and numerical investigations on spray atomization characteristics of an undiluted soybean biodiesel fuel. They investigated spray characteristics and injection delay using images obtained from a visualization system. Also, they determined Sauter mean diameter (SMD) using a droplet analyzer system. In their results, increment and advancement at the peak fuel injection rate were observed while the injection pressure increased. They concluded that these results were due to the increase of the initial injection momentum using soybean biodiesel fuel which has higher density compared to diesel fuel. Also, both fuels showed similar tendencies for the predicted local and overall SMD distribution patterns and spray tip penetration.

In some studies, reformulation of soybean biodiesel fuel compositions has been considered as a way of reducing the increased NO_x emissions. Tat et al. [11] thought that higher NO_x emissions might be resulted from an inherent polyunsaturation characteristic of soybean oils which affects the biodiesel cetane number. Therefore, they tried genetic modification of soybean feedstocks with a high oleic acid (>85%) and reduced palmitic fatty acid (<4%) profile on the increase in NO_x emission problems. In their study, high-oleic soybean biodiesel fuel resulted in significant improvements in NO_x emissions. In another study, Hess et al. [12] used isomerized methyl oleate and isomerized soybean biodiesel at 20% blend level and they provided reductions on the NO_x emissions from 1.5% to 3%. Also, they tried soybean methyl polyol fuel (in 20 vol.%) produced from hydroxyl group adding to double-bond chain by means of oxidizing of soybean oil and reduction about 4.5% was achieved. However, Moser et al. [13] evaluated soybean and partially hydrogenated soybean biodiesel fuels in 20% blend ratio and higher NO_x emissions were found for both of soybean biodiesel fuel types. Also, they concluded that reduction in double bond content in the partially hydrogenated soybean biodiesel did not result in a significant difference in NO_x emissions against the soybean biodiesel fuel level.

These results showed that reformulation strategy of the soybean biodiesel fuels alone cannot be enough to provide solution on the NO_x emission problems while improving other emissions. Therefore, modification of the engine parameters such as different injection strategies and EGR application may be reasonable to provide simultaneous improvements on the emissions due to different physical and chemical characteristics of soybean biodiesel fuels. In a study conducted by Qi et al. [14], the effects of main injection timings with split injection strategy and EGR rates on the combustion and emissions in DI diesel engine were investigated with neat soybean biodiesel fuel. It was reported that increase of the EGR rate and retarded main injection timings were found to be effective methods to reduce higher NO_x emissions resulting from soybean biodiesel fuel usage without more penalties of soot emission and BSFC. In another study, Yoon et al. [15] studied the effects of neat soybean biodiesel fuel on spray, combustion and exhaust emission characteristics in a DI common-rail diesel engine with a cooled-EGR system. In their results, similar fuel injection characteristics such as injection rate and mass results were found for soybean biodiesel fuel with shorter injection delay when compared with diesel fuel. Also, soybean biodiesel fuels had larger SMD and longer spray tip penetration in their microscopic fuel injection results. In addition, similar indicating patterns with peak combustion pressures and peak heat release rates were found with the combustion of soybean biodiesel fuel in their results. It was reported that higher NO_x emissions of soybean biodiesel fuel improved effectively with the EGR application, while soot, HC, and CO emissions were maintained at lower levels.

As seen also from the literature, EGR application is the most widely used technique in diesel engines and has an important role in the efforts on the mitigation of increased NO_x emissions. Therefore, the EGR effects on the combustion, engine performance and exhaust emissions should be considered and investigated. The objective of this study is to provide detailed insights to understand clearly the effects of combining soybean biodiesel fuel addition and EGR application on combustion, engine performance and exhaust emissions and compare with diesel fuel operation.