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Study of combustion, performance and emissions of a diesel engine fueled with ternary fuel in blended and fumigation modes

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ABSTRACT

The present study aimed to compare the combustion, performance and emissions of a diesel engine fueled with diesel, biodiesel and ethanol in the blended and fumigation modes. In addition, a combined fumigation and blended mode (F + B) of fueling was introduced to understand its behavior in comparison with the blended and fumigation modes. In the blended mode, the fuel was composed of 80% diesel, 5% biodiesel and 15% ethanol (DBE), by volume. In the fumigation mode, a mixture of biodiesel and ethanol (BE) was injected into the intake manifold and diesel fuel was used as the main fuel. In the F + B mode, half of the BE mixture was injected into the intake manifold and another half of the DB mixture was mixed with diesel to form the main fuel. The experiments were conducted at a speed of 1800 rpm with five engine loads at a constant mixture percentage of D80B5E15 for the three fueling modes to provide the same fuel composition for comparing the effects of the three fueling modes.

According to the average of five loads, compared to the pure diesel operation, the blended mode causes increases in peak heat release rate (HRR), ignition delay (ID), BSFC, CO, HC and NO_2; drops in duration of combustion (DOC), CO_2, NO_X, PM, total number concentration (TNC) and geometric mean diameter (GMD); and similar peak in-cylinder pressure and BTE. While the fumigation mode leads to higher peak HRR, DOC, BSFC, CO, HC, NO_2 and TNC; lower ID, BTE and NO_X; and similar peak in-cylinder pressure, CO_2, PM and GMD in comparison with the diesel mode. In addition, the F + B mode has the effects between those of the fumigation and blended modes. Among the three fueling modes, the blended mode gives the highest engine performance and lowest emissions, except for NO_X. In contrast, the fumigation mode gives the worst engine performance and emissions, except for NO_X.

1. Introduction

The use of biofuels in diesel engine is an attractive method for reducing reliance on diesel fuel and for reducing engine emissions [1–3]. In particular, the diesel-biodiesel-ethanol (DBE) blend has the potential to be an alternative to diesel fuel for diesel engines [3,4]. DBE is stable even below 0 °C and has identical or superior fuel properties to regular diesel fuel [5]. Also, the addition of biodiesel in the diesel-ethanol blend shows a favorable approach towards the formulation of a novel form of alternative fuel [6], because diesel and ethanol are immiscible. The literature reveals that DBE has been utilized in many studies to investigate its effects on the combustion, performance and emissions characteristics in different types of diesel engines. The findings of these studies have been summarized in the review paper [7]. In addition to the blended mode, biofuels can be applied to a diesel engine in the fumigation mode by injecting the biofuels into the air intake to form a uniform air/fuel mixture inside the engine cylinder [8,9]. Most of the studies concerning fumigation have been conducted by using alcohols (especially ethanol and methanol) as the fumigated fuels and diesel as the main fuel.

Each fueling mode (blended or fumigation) has its advantages and disadvantages [7–9]. For instance, the blended mode causes increase in BTE, decrease in HC and CO emissions but increase in NOx emissions in most cases. On the other hand, the fumigation mode has reverse effects of the blended mode, leading to drop in NO_X but reduction in BTE and increase in HC and CO emissions in most cases. Most of the former studies were conducted either in the blended mode or in the fumigation mode. Only a few studies [10–13] were conducted to compare the effect of these two modes using the same fuel on the same diesel engine and under the same operating conditions. Abu-Qudais et al. [10] compared

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Nomenclature

$\bar{X}_i$	Sample observation
$X_1, \cdots, X_N$	Independent variables
X_m	Mean of measurements
$\omega_1, \cdots, \omega_N$	Uncertainties of independent variables
ω_R	Uncertainty of the result
ω_r	Random error
ω_s	Systematic error
°CA	Crank angle degree
B	Biodiesel
B20	20% biodiesel + 80% diesel
B20 + FG	(20% biodiesel + 80% diesel) + fumigated gasoline
BE	Biodiesel-ethanol
BSCO	Brake specific carbon monoxide
$BSCO_2$	Brake specific carbon dioxide
BSFC	Brake specific fuel consumption
BSHC	Brake specific hydrocarbon
$BSNO_2$	Brake specific nitrogen dioxide
$BSNO_X$	Brake specific nitrogen oxides
BSPM	Brake specific particulate matter
BTDC	Before top dead center
BTE	Brake thermal efficiency
C	Carbon
CI	Compression ignition
CPC	Condensation particle counter
D	Diesel
D + FG	Diesel + fumigated gasoline
DBE	Diesel- biodiesel- ethanol
DI	Direct injection
DMA	Differential mobility analyzer
DOC	Duration of combustion
DR	Dilution ratio
E	Ethanol
EOC	End of combustion
F + B	Fumigation + blended mode
FC	Fuel consumption
FG	Fumigated gasoline
GMD	Geometric mean diameter
H	Hydrogen
HCLD	Heated chemiluminescent analyzer
HFID	Heated flame ionization detector
HRR	Heat release rate
Hz	Hertz
ID	Ignition delay
min	Minute
N	Particle number
NDIR	Non-dispersive infrared analyzers
Nm	Newton meter
nm	Nanometer
O	Oxygen
pC	Pico coulomb
R	Function
rpm	Revolutions per minute
SMPS	Scanning mobility particle sizer
SOC	Start of combustion
TEOM	Tapered element oscillating microbalance
THC	Total hydrocarbon
TNC	Total number concentration
ULSD	Ultra-low-sulfur diesel
N	Number of samples
SD	Standard deviation
U	Total uncertainty
t	Student's t statistic
ν	Degrees of freedom

the effects of ethanol fumigation and ethanol-diesel blends on the performance and emissions of a single cylinder diesel engine under different engine speeds, using 20% of ethanol blended with diesel and 20% of ethanol (ethanol percentage as a fraction of the diesel energy input at full rack setting) in the fumigation mode. They found improvement in BTE and soot emission but increase in HC and CO emissions in both modes of operation compared to the operation with pure diesel fuel; while the fumigation mode showed higher BTE and lower CO, HC and soot emissions, in comparison with the blended mode. However, their investigation did not involve NOx and PM emissions. Cheng et al. [11] compared the influences of 10% blended methanol (by volume) or 10% fumigation methanol with waste cooking oil biodiesel on the performance and emissions of a diesel engine at a constant engine speed of 1800 rpm with five engine loads. Their results indicated, compared to the diesel fuel operation, there was a reduction of CO_2, NO_X, particulate mass emissions and mean particle diameter in both modes of operation; while CO and HC emissions were similar in the blended mode but higher in the fumigation mode. Compared to the blended mode, the fumigation mode gave slightly higher BTE at medium and high engine loads and lower NOx emission, but there was also higher CO, HC and NO_2 and particulate emissions. Şahin et al. [12] compared the impact of n-butanol/diesel blends and n-butanol fumigation on the performance and emissions of a turbocharged diesel engine, using 2, 4, and 6% by volume of n-butanol, under different engine loads and engine speeds. It was found that both modes led to reduction in smoke compared to the diesel fuel while the reduction was higher in the fumigation mode. Compared to the diesel fuel, NO_X emission was lower in the fumigation mode but higher in the blended mode; HC emissions were higher in both modes, being higher in the fumigation mode than the blended mode; and similarly, CO_2 emissions were increased for the two modes, being lower in the fumigation mode than the blended mode. In regard to BSFC, fumigation caused rise in BSFC at all test conditions, while the blended mode led to reduction in BSFC for 2% and 4% n-butanol blends (6% n-butanol blend caused increase in BSFC). Also, the HRR diagrams of the blended mode were similar to those of diesel fuel; however, those of the fumigation mode had a double peak structure. The first peak, which was small, occurred earlier than that of diesel fuel and the second peak, which was also the main peak, took place later. Their investigation did not involve PM emissions. Also, Mariasiu et al. [13] studied the performance and emissions of a single cylinder diesel engine using a diesel fuel containing 5% by volume of rapeseed biodiesel, a blended fuel containing 85% of the diesel fuel and 15% by volume of ethanol and the diesel fuel with fumigated ethanol under a constant speed of 1800 rpm and different engine loads. It was found that the fumigation mode had lower BSFC, NO_X and THC, and higher CO emissions compared to those of the blended mode. However, their investigation did not involve PM emissions.

According to the literature, only alcohol fuels were utilized in the fumigation mode and the use of biodiesel + alcohol as a fumigated fuel almost cannot be found. Since DBE is a widely investigated blended fuel, there is an interest to apply it in the fumigation mode to identify its advantages and disadvantages in comparison with the blended mode. Therefore, this study aims at covering the above knowledge gaps by conducting experiments to compare the effect of using blended mode (DBE as the fuel) with fumigation mode (BE as the fumigated fuel and diesel as the main fuel to form DBE) on the engine combustion, performance and emissions. Moreover, an additional mode of operation, using 50% of the BE blended with the diesel fuel and applying another 50% of the BE mixture in the fumigation mode (namely F + B mode), is also introduced for comparison with the other two modes. According to