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Investigating the influence of additives-fuel on diesel engine performance and emissions: Analytical modeling and experimental validation

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HIGHLIGHTS

- Modeling of engine performance by applying the statistical technique.
- Rigorous optimization of additives–diesel fuel formulation.
- Model verification and accuracy analysis based on performance factors.
- Decrease of soot emission and increase of engine performance.

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ABSTRACT

In this study, the effect of ethanol–diesel blends with different types of additives on performance and exhaust emission is experimentally investigated through experimental modeling and optimization methods. Experiments are performed on a turbocharged common rail direct injection (CRDI) engine. The modeling is used to optimize the emission, engine performance, and physico-chemical properties by implementing factorial design considering four main parameters, namely, choice of oxygenate and nitrogenate such as Nitroethane (NE), Nitromethane (NM) and 2-methoxy ethyl ether (MXEE) and metal additives such as Manganese (MN) and Cerium (CE), engine speed (2200 and 1500 rpm) and load (370, 275, 180 and 20 N m). Findings by modeling show that the quadric and cubic terms of these four variables had significant effects. The obtained results prove that using the diesel–ethanol–(NE + MN) is better to decrease soot emissions and increase cetane number. The properties under study were cetane number and viscosity experiment. The emissions decrease with increasing the engine speed. The effect of blending (MXEE + CE) with diesel–ethanol on improvement of the engine performance is higher than other additives. The optimal conditions are found to be the NE, MN, engine speed and load of 1500 rpm and 168 N m, respectively. Under these conditions, the model estimated the soot content, formation of NO_x and CO_2, brake specific fuel consumption (BSFC) and powers of 27.6, 441.3, 28.1 ppm, 224.2 g/kW h and 26.5 kw, respectively. The modeling techniques and developed models can be employed as a useful tool for design and optimization of appropriate ethanol–diesel fuels with effective performance for various industrial applications.

1. Introduction

Diesel fuel is a petroleum-based fuel, which consists mainly of aliphatic hydrocarbons C_{8-28} with boiling temperatures varying from 130 to 370 °C [1]. Diesel engines are widely used for many applications due to their efficiency, adaptability, reliability and etc. Exhaust emissions from diesel Engines contain various kinds of air pollutants, such as air unburned total hydrocarbon (UTHC), nitrogen oxides (NO_x), particulate matter (PM), and carbon oxides (CO) [2,3]. The environmental issues of global warming, climate change and widespread use of fossil fuels have greatly added to the interests for investigation of the applications of renewable fuels in internal combustion engines. For emissions regulations, researches have concentrated on the both of engine and fuel-related techniques [4–6], including with a blend of oxygenated fuels that can reduce particulate emissions [7–13]. The performed studies have mainly focused on improvements in the combustion

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Nomenclature

$b_0, b_1, \ldots, b_n$	regression coefficients	X_1, X_2, X_3	coded variables
DOF	degree of freedom	$\overline{X}$	mean value of variables
F-value	ratio of variances, computed value	*Y*	response
i and *j*	subscripts (integer variables)	BSFC	brake specific fuel consumption
n	number of factors (variables)	CI	cetane index
P-value	statistical criterion	MXEE	2-methoxy ethyl ether
CV	coefficient of variation	NM	Nitromethane
R	correlation coefficient	NE	Nitroethane
R^2	coefficient of multiple determinations	CE	Cerium
R^2_{adj}	adjusted statistic coefficient	MN	Manganese

and exhaust emissions performance when diesel–ethanol blend fuel is used. To use ethanol in diesel engine, various methods were developed such as direct blending [14–16], fumigation [17–19], emulsification [20,21], and sometimes dual ignition [22]. The problem of dissolving ethanol in diesel and the firmness of blends is influenced by the water content, using of high percentage of ethanol, and ambient temperature below 10 °C. On the other hand, ethanol has a low cetane index and number, which leads to a lower cetane index of ethanol–diesel fuel that makes auto-ignition difficult and gives a long ignition delay. In conventional studies, it was rather difficult to get a quality of ethanol–diesel fuel by direct injection, but the problem can now be solved by adding tertiary additives, such as nitro ethane, nitro methane, 2-methoxy ethyl ether, methyl ester [23–26] and other additives. So many studies on the engine performance, fuel properties and emission characteristics of diesel engine running with diesel–ethanol blend have been conducted. Yage et al. [22] performed a study on the influences of ethanol–diesel blend in rate of 6–24% by volume of ethanol. Test engine was run between 1800 and 2400 rpm. Experimental results indicated that particulate matter and brake thermal reduced. Huang et al. [27] examined the effect of ethanol addition for 10–30% and engine speeds 1500 and 2000 rpm. The results demonstrated that NO_x, CO, HC and BSFC increased. Devaradjane and Gnanamoorthi [28] investigated the effect of ethanol–diesel on performance and exhaust emissions. 1% of ethyl acetate and 1% diethyl carbonate were added to the blend. The results revealed that brake thermal efficiency (BTE) in this blend was higher than that of neat diesel. However, the soot emissions decreased with this blend, but NO_x and CO emissions increased.

Gargiulo et al. [29] explored chemico-physical features of the soot emitted from a dual-fuel (DF) ethanol–diesel system. They showed a significant effect of ethanol with fumigation method of blending on the concentration of the emitted particles but on the average size, as well as a very low impact (negligible) of ethanol blended charge on the soot Nano structural features. Cheng and coworkers [30] studied the influence of oxygenates mixed with the diesel fuel on the particulate matter emission in a compression–ignition engine, and they reported that the reduction of particulate matter was only correlated to the oxygen content of the blend with the PM being reduced by about 3.5% for 1% fuel oxygen. Herreros et al. [31] researched the effect of ethanol–diesel blended with an additive having a high cetane number (diethylene glycol diethyl ether) on reduction of the air pollutions. They showed that the PM (particulate matter) decreased, but CO, HC and NO_x increased as compared to the diesel fuel.

Based on this background, finding more effective/better formulations for the diesel and optimization of the fuel properties, have been needed to break through the trade-off relation for reducing the soot and NO_x emissions, improvement of the diesel combustion processes, and exhaust emissions. Therefore, the main purpose of this research is to investigate the influence of different variables such as type of oxygenate and nitrogenate additives and cetane improver, engine speed and load on combustion performance. Experimental studies were concentrated to test the performance of different additive–ethanol–diesel fuel blend with tertiary additives such as nitro ethane, nitro methane and 2-methoxy ethyl ether for reduction of the soot and other exhausts, as well as engine performance and cetane number improvement. Toward this end, this is the first study of its kind that is conducted on experimental study and modeling development with optimization of the exhaust emission, fuel properties and performance engine on diesel by applying the statistical technique. The experimental results of this research can confirm that nanoparticles (MN and CE) can contribute to reduce the air pollution and enhance the engine performance, while nitro ethane with manganese was found superior on the soot reduction with much smaller effect on the engine performance. However, experimental results showed that using 2-methoxy ethyl ether with cerium was better for the engine performance. As a result, this research shed light on the factors of fuel formulation in the context of further exploitation of the tertiary additives–ethanol–diesel blend fuels for pollution reduction and related industrial applications.

2. Experimental techniques and methodology

2.1. Engine and experimental set-up

The baseline engine that used, was a 4-cylinders, inter cooled and turbocharged, with direct injection (DI) and an aspirated diesel engine (MT4.244) with 3.99-L displacement, 100-mm × 127-mm bore × stroke and 17.5 compression ratio with a peak power output of 61.5 kW at 2200 rpm.

The ethanol used in these tests was actually limited to anhydrous ethanol because the hydrous ethanol was insoluble or with a very limited solubility in the high percentage of diesel fuels. Commercial diesel fuel and analysis-grade anhydrous ethanol (99.8% purity) were used for this purpose. Three different additives that have high cetane number (NM, NE, MXEE) with two different Nano metallic additives (MN, CE) were added into the ethanol–diesel fuel. The cetane index (CI) can be calculated according to ASTM D 4737. The physico-chemical properties of the diesel fuel and oxygenated compounds used in the formulation are shown in Table 1. However, the general factorial experiments design matrix with related variables and levels are shown in Table 2.

2.2. Operating conditions

The effects of additive–ethanol–diesel blends with metal additives on fuel properties, engine performance and exhaust emis-