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# Assessment of a direct injection diesel engine fumigated with ethanol/water mixtures

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Enhancing the combustion process of today's diesel engines necessitates finding practical methods to reduce harmful emissions, with minor modifications on the main structure of the engine. Dual fuel method has been recognized as an effective way that be able to resolve the emissions problems encountered in diesel engines and attain higher performance. An experimental investigation is performed to explore the effects of using ethanol/water mixtures fumigation into the inlet air on the performance and exhaust emissions of a fully instrumented single cylinder diesel engine. Ethanol/water with different mixing ratios (25%, 50%, 75% and 100% by volume) are used as a secondary fuel with diesel as the main fuel. Fuel consumption, exhaust gas temperatures and exhaust emissions such as nitrogen oxides, carbon monoxide and unburned hydrocarbons are measured and compared for both methods of operation. In addition, thermal and exergy efficiencies are calculated and compared. The results indicated that NO emission tend to decrease with mixtures containing water and tend to slightly increase with pure ethanol fumigation. CO, HC emissions and fuel consumption tend to increase while exhaust gas temperatures tend to decrease with all mixtures of ethanol/water fumigation. Slight improvements in thermal and exergy efficiencies with ethanol/water mixtures fumigation are found. Results confirmed the potential use of ethanol/water fumigation in diesel engines for better energy and exergy efficiencies and lower NO emission.



## 1. Introduction

Rapid reduction of fossil fuels and their harmful effect on the environment forced the need for searching alternative fuels that can be capable to meet energy requirements and emission regulations. In this regard, the need of alternatives such as biofuels is increasing in order to replace the continuously depleted fossil fuels. Among the biofuels, alcohols have proven to be capable of working successfully as alternative fuels owing to their storage facility, availability and handling.

Alcohols, especially ethanol, have been recognized as suitable fuels for spark ignition engines due to its high octane number. However, ethanol is difficult to be used as a fuel in compression ignition engines due its low cetane number. Therefore, researchers tried to find suitable ways to incorporate ethanol into the compression ignition engines [1].

Ethanol can be introduced into diesel engines by using various methods; the most common ones are blending and fumigation. In blending method, ethanol and diesel fuels are premixed uniformly and then injected directly into the engine cylinder using the same diesel fuel injector [2–7]. The miscibility of ethanol with diesel fuel can be stabilized by using suitable additives. One of the main disadvantages with this method is the limited quantity of ethanol which can be blended with diesel. When ethanol is mixed with diesel, physical properties of both fuels will be affected. For example, the viscosity as well as cetane number and heating values of diesel fuel will decrease [1].

These issues can be resolved by using fumigation techniques through which ethanol fuel is directly introduced into the intake air [8–11]. This method of introduction has the advantage of improving air utilization through the increase of air density, since the addition of ethanol lowers the intake mixture temperature. Increasing the amount of air in the cylinder can increase power generation provided that suitable amount of fuel is used [1]. In addition, only minor modification such as adding low pressure fuel injector, additional fuel tank, lines and controls are required [12]. Furthermore, fumigation permits a relatively large amount of

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**Nomenclature**

| | |
|---|---|
| BSFC | brake specific fuel consumption (g/(kW h)) |
| $\dot{E}x$ | exergy rate (kW) |
| $H$ | heating value of fuel (kJ/kg) |
| $\dot{m}$ | mass flow rate (kg/s) |
| $P$ | power or work rate (kW) |

*Greek letters*

| | |
|---|---|
| $\eta$ | thermal (energy or first law) efficiency (%) |
| $\Psi$ | exergy (second law) efficiency (%) |
| $\varphi$ | chemical exergy factor or quality factor (-) |
| $\varepsilon$ | specific fuel exergy (kJ/kg) |

*Subscripts*

| | |
|---|---|
| $B$ | break |
| $D$ | diesel |
| $E$ | ethanol |
| $in$ | inlet |
| $u$ | lower |
| $W$ | work |

ethanol fuel to replace diesel fuel without sacrificing engines performance characteristic.

Numerous researchers studied the effects of ethanol fumigation on the performance and exhaust emissions of diesel engines. Recently, Imran et al. [12] conducted a comprehensive review on the potential use of alcohols in fumigation mode on diesel engine.

Jiang et al. [13] studied the effects of ethanol fumigation on the flame temperature and nitrogen oxides (NOx) emissions of a four-cylinder, turbocharged diesel engine. They found that NOx emission was reduced significantly with ethanol fumigation. The decrease in NOx emission was attributed to the reduction in flame temperature as well as changes in the combustion mode.

Abu-Qudais et al. [14] performed an experimental study in a single cylinder diesel engine to investigate the influences of using either ethanol fumigation or ethanol–diesel blends on the performance and emissions of modified engine. The results indicated that the engine performed better with fumigation method. The percentage of ethanol needed for better performance and emissions was optimized and found to be approximately 20%.

Ekholm et al. [15] applied ethanol fumigation to a 12 L six-cylinder heavy-duty diesel engine. NOx emissions of 0.1 g/kW h and relatively high brake thermal efficiency of 38% were obtained and stable combustion was achieved at medium load. Corresponding values of NOx emissions and brake thermal efficiency of 0.34 g/kW h and 38%, respectively, were obtained at high load operation.

Janousek [16] performed an experimental work to investigate the effect of ethanol and water fumigation on the efficiency of a 4-cylinder diesel engine at various engine speeds. It was reported that the thermal efficiency with fumigation was slightly different from that with the only diesel operation. However, NOx emissions were reduced significantly while CO and HC emissions were increased with ethanol fumigation.

Surawski et al. [17,18] tested a 4-cylinder naturally aspirated diesel engine fumigated with ethanol and their results showed an increase in CO and HC emissions, while a reduction in NO emissions was observed.

Chauhan et al. [1] investigated the effects of ethanol fumigation in a small capacity diesel engine on exhaust emissions, under various load conditions. Results indicated that the ethanol fumigation resulted in a reduction in NOx, CO, carbon dioxide ($CO_2$) and exhaust temperature, while HC emission was increased for all engine loads examined.

Goldsworthy [19] tested the effects of fumigating vaporized ethanol–water mixtures (93%, 72% and 45% by mass) in a constant speed and various loads (BMEP of 17 bar and 20 bar) diesel engine operating with two stage injection. Small improvement was detected in brake thermal efficiency with 72% mixture at a BMEP of 20 bar. They reported that when ethanol addition was increased CO emissions and exhaust opacity were increased, while NOx emission was decreased. A reduction on NOx emission was also observed with the increase in water content.

Di Blasio et al. [20] conducted an experimental research on a single cylinder light duty diesel engine to study the engine performance and exhaust emissions using ethanol–diesel working under dual fuel operation. At medium and high load, their results showed the potential of using ethanol fumigation in reducing emissions such as NOx and soot while improving the thermal efficiency. However, HC and CO emissions were increased significantly at low load.

Padala et al. [12,21] investigated the performance and emissions characteristics of a single-cylinder diesel engine fumigated with ethanol at medium load. Results indicated that the engine efficiency was increased (by 10%) with the increase in ethanol energy fraction [21]. The maximum value of diesel energy that could be replaced by ethanol was 60% after which the operation was limited due to misfiring. The emission results indicated that HC, CO and NOx emissions were increased with increasing ethanol fraction.

Hansdah and Murugan [22] carried out experimental investigations in a single cylinder diesel engine, fumigated with different flow rates of bioethanol using a vaporiser and injector. The observed results suggested an optimum value of 0.48 kg/h of bioethanol fumigation to achieve better performance and lower emissions.

Tutak [23] and Sarjovaara and Larmi [24] investigated the potential use of fumigating E85 fuel in a direct injection diesel engine. Results showed that, with the fumigation of E85 fuel, NOx and soot emissions were reduced, while CO and HC emissions were increased significantly.

Sahin et al. [25] experimentally examined the effects of using ethanol fumigation on engine performance, smoke index K and NOx emission of a turbocharged indirect injection automotive diesel engine. Experimental results showed that ethanol fumigation can successfully improve engine performance and at the same time reduce smoke index K and NOx emission.

Using of low-proofs (aqueous) ethanol fumigation is economically advantageous since the production process can be done in small distillation facilities and amount of energy spent in dehydration can be eliminated. This important issue of fumigating ethanol with different proofs (such as 200, 190, 180, 160, 150, 140 and 100) was addressed by various researchers [26–32]. The most common findings of these researches were:

1. The levels of NOx emission was decreased, especially when fumigating the lower proofs.
2. Although HC and CO emissions were greatly increased, ethanol proof did not have any significant effect on them.
3. Ethanol fumigation resulted in longer ignition delays and higher rates of pressure rise. The rate of pressure rise was reduced when fumigating ethanol with lower proofs.
4. Brake thermal efficiency would either exhibit a slight increase at high loads or a slight decrease at low loads.