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The Effect of Adding EN (2-Ethylhexyl Nitrate) to Diesel-Ethanol Blends on Performance and Exhaust Emissions

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Abstract

In this study, effect of 2-ethylhexyl nitrate (EN) addition to diesel-ethanol blends as cetane improver were examined with regard to performance parameters such as brake torque, brake power, brake specific fuel consumption and exhaust emissions such as NOx, CO, CO_2 in a four-cylinder, water-cooled diesel engine. Firstly, an ethanol-diesel blend represented as E10 were prepared by mixing 10% of ethanol with 90% of diesel fuel as volume. Then other blends symbolized as E10EN2 (10% ethanol, 2% EN and 88% diesel), E10EN4 (10% ethanol, 4% EN and 86% diesel) and E10EN6 (10% ethanol, 6% EN and 84% diesel) were created by mixing ethanol-diesel-EN to get information about the behavior of EN. The results obtained for these blends at five different engine speeds under full load condition were compared with E10 and 100% diesel fuel. It was found that EN addition raised the cetane number by 5%, 11%, 16% for E10EN2, E10EN4 and E10EN6 compared to E10 whereas EN caused a slight decrease in kinematic viscosity, lower heating value and a slight increase in density. It was also deduced that EN addition had a reducing effect on NOx, CO emissions and brake power while it had an increasing effect on CO_2 emission and brake specific fuel consumption.

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1. Introduction

Diesel engines are internal combustion engines in which fuel is injected on pressurized hot air within the cylinder by compression in order to obtain the heat required for ignition. In these engines, combustion occurs where the ignition conditions are optimum with self-ignition of fuel-air mixture at the end of a certain ignition delay period following the injection of fuel. The longer ignition delay period, which means it requires more time to complete combustion, leads to uncontrolled combustion of the fuel-air mixture causing an increased amount of fuel air mixture taken into the cylinder. This phenomenon which occurs with the sudden pressure rise causing the engine to work harder and noisy is known as diesel knock. There are many parameters that affect the ignition delay period/diesel knock. These are ambient temperature, ambient pressure, which are two main factors. Besides these, operational factors such as engine speed, intake air temperature and pressure, engine load and oxygen concentration, structural factors such as compression ratio, engine cooling conditions, injection quality and fuel factors have also effect on diesel knock [1]. When evaluated in terms of fuel, the most important parameter is cetane number which is a measure of fuel ability to self-ignition and it is affected by the molecular structure and composition of the fuel [2]. When it is desired to increase ignition ability of fuel, it is needed to prevent diesel knock and shorten the ignition delay period or in other words to ensure an increase in cetane number.

As it is known, when depletion risk of fossil fuel is thought to be associated with increasing energy costs and demands, seeking for alternative energy sources is emerged in transportation as in others. Ethanol is just such an alternative to diesel fuel with the feature of being produced from renewable sources and having potential to reduce exhaust emissions originated from diesel engines. But direct use of ethanol creates some drawbacks such as lower heating value, poor lubrication properties etc. [3]. So the opinion of using ethanol blending with diesel fuel comes to mind in order to overcome these drawbacks. Although addition allows the use of ethanol in diesel engine, ethanol-diesel blends are faced with low cetane number. Thus, adding ethanol to diesel fuel is one of the situations that cetane number is necessary to increase by lowering aromatic content of the fuel via hydro treating or by cetane improver addition which is more cost effective way than the other [4].

Cetane improvers can be classified as peroxides, nitrites, nitrates, nitroso-carbamates, tetra-azoles, and thioaldehydes [5]. These additives shorten the ignition delay period between injection fuel and combustion where the various physical and chemical reactions occur such as atomization, evaporation, mixing with air [6]. The most commonly used one is 2-ethylhexyl nitrate (usually abbreviated as EHN, 2EHN or EN), which improves combustion characteristics, lower the burning point and shorten ignition delay [7].

Some of the studies related with EN are summarized below. Zhang et al. [7] have used a single-cylinder heavy-duty diesel engine fueled with D40 (40% DMF (2,5-dimethylfuran) by vol.) with 2% EN addition. Results have showed that ignition delay has shortened with EN addition and maximum pressure increase rate has decreased linearly with the ratio of EN. While EN addition increases NOx emission, it greatly decreases THC emission with high EGR rate. Based on their results, it has also been stated that EN addition to D40 has solved trade-off problem between combustion noise and soot emission for low cetane number oxygenated fuels. Ickes et al. [8] have investigated the effect of a direct injection, diesel engine LTC operating mode fueled with diesel fuel doped with EN. It has been detected that adding EN to the fuel increases NOx emission for premixed LTC. In another study, İleri and Koçar [9] have examined the effect of adding antioxidants, butylated hydroxyanisole (BHA), butylated hydroxytoluene (BHT), tert-butylhydroquinone (TBHQ) and 2-ethylhexyl nitrate (EN) to B20 biodiesel/diesel blend. It has been observed in their study that addition of antioxidants decrease brake specific fuel consumption. It has been stated that EN is the best of all to reduce the NOx emission (4.63%) and each antioxidant leads to an increase in CO emission. Li et al. [10] have examined the effect of three different cetane improvers (2-ethylhexyl nitrate, cyclohexyl nitrate and 2-methoxyethyl ether) by adding 0.3% of each to B90M10 methanol/biodiesel blend. It has been confirmed that cetane improvers increase HC and CO concentrations while they reduce NOx concentration and smoke. Furthermore no matter they have added, it has not observed any effect on brake thermal efficiency and exhaust temperature. Hess et al. [11] have examined the effect of adding 1000 ppm of several cetane improvers, one of which is EN, to B20 biodiesel/diesel blend. As a result of study, it has been reported that EN addition reduces NOx emission by about 4.5%. Atmanli [12] has examined the effect of EN addition at 500, 1000 and 2000 ppm concentration to DnBH and DPnH (70% diesel, 20% hazelnut oil, 10% n-butanol or 10% 1-pentanol by vol.) micro emulsions on fuel properties and diesel engine characteristics. Tests have been performed under five different engine loads (0%, 30%, 60%, 90% and 100%) at 2200 rpm constant engine speed. It has been obtained that EN addition has no significant effect on density, kinematic viscosity, cloud point, cold filter plugging point (CFPP) or flash point but it has led to an increase in cetane number of DnBH and DPnH by about 13% and 12% for respectively. It has also confirmed that EN addition decreases brake specific fuel consumption and nitrogen oxide (NOx) emission significantly while it has caused to increase in carbon monoxide (CO) emission. Ileri [13] has investigated the effect of 2-ethylhexyl nitrate on engine performance and exhaust emission of a diesel engine fueled with D70S20P10 and D70S20B10 (diesel/sunflower oil/n-butanol or 1-pentanol blends). Results of the study are as follows: Adding EN to micro emulsion blends has little effect on brake power and brake mean effective pressure while it produces lower NOx, higher CO emission. As EN concentration increases, brake specific fuel consumption reduces. Relekar et al. [14] have conducted an experimental study to determine the best percentage of various additives which ensure maximum efficiency and minimum emission. For this purpose, experiments have been performed with five samples obtained by blending three different additives. As a result, it has been expressed that best percentages are 70%, 15%, 15% for dimethyl carbonate, ethyl acetate, and 2-ethylhexyl nitrate as fuel additive.

As mentioned above, there are many studies related to EN in the literature. These are focused on especially reducing NOx emission and increasing the cetane number. In this study, the effects of EN addition in different ratios (2%, 4%, 6% by vol.) to ethanol-diesel blends on diesel engine performance and exhaust emissions has been investigated. Performance parameters are brake torque, brake power and brake specific fuel consumption, exhaust emissions are CO, CO_2 and NOx emissions. The results were compared with E10 and the reference diesel fuel.

2. Material and Methods

The experiments were performed on a four-cylinder, water-cooled diesel engine. Other specifications of the engine are given in Table 1.

Table 1. Engine specifications

Engine name	Basak engine
The number and type of cylinders	4 cylinder – inline
Cylinder volume, lt	2.8
The engine speed range (rpm)	750 – 2100
Max. Torque, Nm @ engine speed	225 @ 1100
Max. Power, kW @ engine speed	45 @ 1700
Cooling system	Water-cooled

Ethanol procured from Konya Sugar Refinery, and diesel fuel obtained from a gas station were used for tests and they were performed at five different engine speeds (800, 1100, 1400, 1700, 2000 rpm) using diesel fuel, E10 (10% ethanol and 90% diesel), E10EN2 (10% ethanol, 2% EN and 88% diesel), E10EN4 (10% ethanol, 4% EN and 86% diesel) and E10EN6 (10% bioethanol, 6% EN and 84% diesel) under full load condition. Fuel properties used during the tests are given in Table 2 in detail. It can also be seen the effect of EN addition to fuel properties from this table.

Table 2. Fuel Properties

Fuel / Properties	Density at 20° C (g/cm^3)	Kinematic viscosity at 40° C (mm^2/s)	Lower heating value (MJ/kg)	Cetane number
Diesel	834.5	2.794	43.14	55.2
Ethanol	816.0	1.370	27.16	-
E10	832.8	2.656	41.54	51.4
E10EN2	835.4	2.631	41.34	54.2
E10EN4	838.1	2.611	41.14	57.0
E10EN6	840.8	2.591	40.95	59.8

3. Result

3.1. Engine Performance

Performance parameters such as brake torque, brake power, brake specific fuel consumption of a diesel engine running at 800, 1100, 1400, 1700, 2000 rpm under full load condition have been evaluated for ethanol, EN and diesel blends in comparison with E10 and diesel fuel as reference.

The variation of brake torque and brake power with engine speed for each test fuel has been shown in Figure 1 and Figure 2. Maximum torque has been obtained at 1100 rpm as 185, 181.8, 181.7, 176.9, 179.6 Nm while maximum brake power has the output value of 27.7, 26.8, 27.1, 26.0 and 24.6 at 1700 rpm for diesel, E10, E10EN2, E10EN4 and E10EN6 respectively. As it is seen, for all engine speeds, higher brake power values have been obtained for diesel fuel as well as brake torque and average decreases in brake power compared to diesel fuel are obtained approximately as 4.88%, 6.24%, 14.34%, 10.52%. The reasons for reducing engine power are lower cetane number and calorific value when ethanol is used. When the effect of EN addition has been assessed, average brake power value of E10 is higher than E10EN2, E10EN4 and E10EN6 as in brake torque. So it can be concluded that EN addition to fuel improves combustion by increasing the cetane number it also leads to reduction of performance along with lower heating value. Variation of brake specific fuel consumption with engine speed for each test fuel is given in Figure 3. The average brake specific fuel consumption is more than approximately 6.5% for E10, 19.2% for E10EN2, 63.1% for E10EN4 and 41.2 % for E10EN6 compared to diesel.

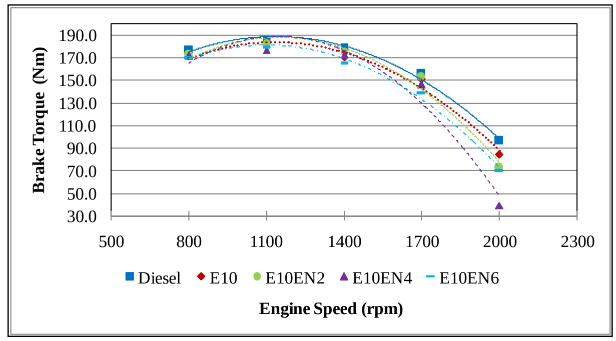

Figure 1. Variation of brake torque with engine speed

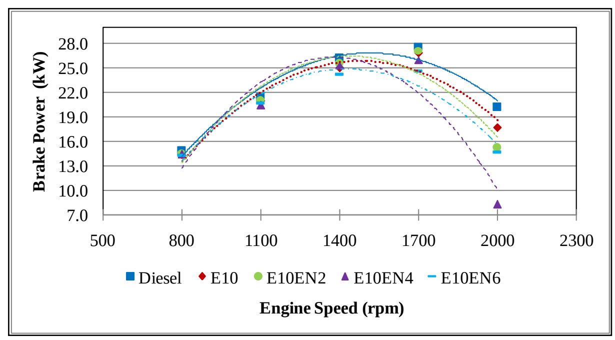

Figure 2. Variation of brake power with engine speed

Namely, the amount of fuel required to generate the same work is less than for the engine fueled with diesel. It can be explained by lower calorific value of diesel being higher than ethanol. Presence of EN in the fuel achieves higher brake specific fuel consumption compared to E10. This is the result of combined effect of lower heating value and density.

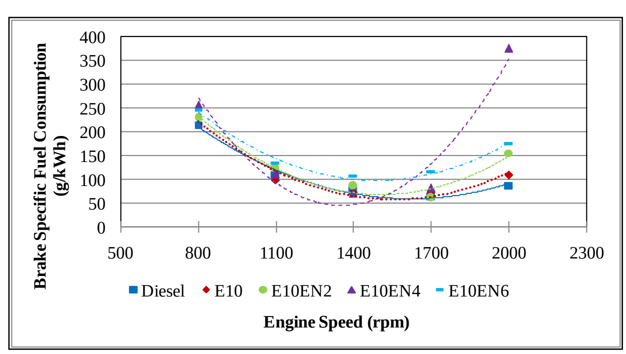

Figure 3. Variation of brake specific fuel consumption with engine speed

3.2. Exhaust Emissions

The variation of CO emission, obtained by using diesel, E10, E10EN2, E10EN4 and E10EN6 as fuel in the test engine, with respect to engine speed is given in Figure 4. As seen, CO emission has shown a downward trend as engine speed generally increases and maximum CO emission is obtained when operating with diesel at all engine speeds. Average decrease of CO emission is 7.93%, 20.54%, 19.34%, and 9.01% for E10, E10EN2, E10EN4, E10EN6 respectively compared to diesel. Because of the high oxygen content of ethanol, it is an expected result that CO emission is lower for fuels containing ethanol within itself. The same relation is also in existence between CO emission and EN content in the fuel. This means that EN has a reducing effect on CO emission compared to E10. But it cannot be said that the increase in the EN ratio causes the increase in CO emission. The major to smallest ranking in terms of CO emission is as follows: By taking the average of all engine speeds, the decrease in average CO emission is 13.69%, 12.39% and 1.17% for E10EN2, E10EN4 and E10EN6 compared with E10. Thus it appears that the optimum EN ratio from the point of view of CO is 2% with E10EN2.

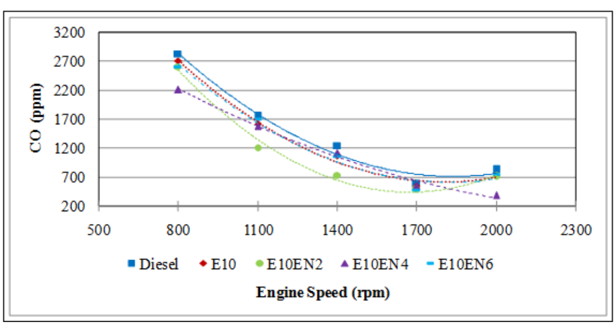

Figure 4. Variation of CO emission with engine speed

Figure 5 shows the variation of CO_2 emission depending on engine speed and fuel. Minimum value of CO_2 emission has been obtained at 2000 rpm while CO_2 emission has the maximum value at 1100 rpm, where engine torque has the highest value, except for E10. When it is assessed in terms of fuel, for all engine speeds, diesel has the highest value for CO_2 emission while minimum of it has been obtained for E10 at low rpm. The decrease in average CO_2 emission is 20.22%, 7.72%, 17.10% and 18.20% for E10, E10EN2, E10EN4 and E10EN6 compared with diesel fuel. While E10 emits less CO_2 emission than diesel, it is revealed that more CO_2 emission is emitted in case the engine operates with fuel containing EN than E10. As EN content in the fuel increases, CO_2 emission also decreases. Therefore it can be deduced that the optimum ratio of EN is 6% for less CO_2 emission.

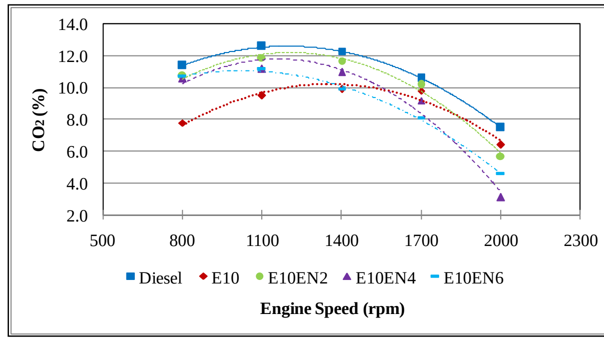

Figure 5. Variation of CO_2 emission with engine speed

The fact is that NOx emission is unavoidable if the maximum temperatures in the cylinder during combustion are too high. While high temperature is the first precursor to the formation of NOx emission, presence of O_2 is the second. Ethanol contains about 34.8% oxygen [15-18]. This content reduces the temperature at the end of the combustion of ethanol. Therefore, exhaust gas temperature decreases due to the oxygen content of ethanol [16,19,20]. NOx emission has reduced due to the decreasing exhaust gas temperatures with ethanol addition to diesel fuel. He et al. [21], Rakopoulos et al. [22], Huang et al. [23] and Lei et al. [24] have presented quite similar results. Cetane improver has minimized the negative effect on combustion of ethanol addition by increasing the cetane number. Although low-ratio cetane improver added into the blend has decreased NOx emission and as the cetane improver content continues to increase, NOx emission has also increased. This case can be explained by the fact that increased ignition delay with ethanol addition has decreased by the addition of the cetane improver. Therefore, combustion efficiency and exhaust gas temperature has increased with rising the temperature at the end of the combustion of fuel [25-27].

As it is seen in Figure 6, NOx emission reduces while engine speed increases. The maximum values of it have been obtained at 800 rpm while it has the lower value at 2000 rpm, maximum engine speed, for all fuels. When considering fuels, it can be seen that fuel which causes maximum NOx emission is diesel fuel for all engine speeds. When each engine speed is evaluated within its own, EN concentration has a positive effect on NOx emission in association with the increase in engine speed. The average NOx emissions are 882 ppm, 742 ppm, 627 ppm, 615 ppm, 748 ppm for diesel, E10, E10EN2, E10EN4 and E10EN6 respectively.

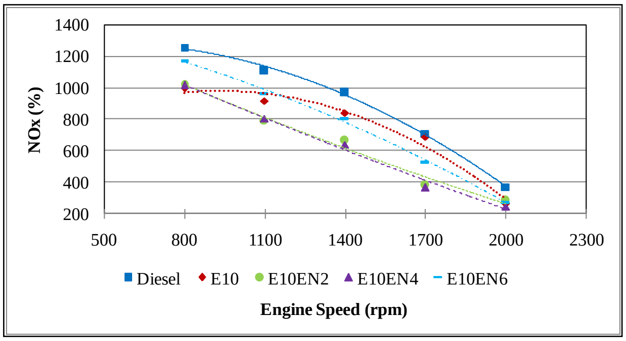

Figure 6. Variation of NOx emission with engine speed

4. Conclusions

In this study, it has been investigated the use of diesel and ethanol blends doped with EN, which is the best known cetane improver, in a diesel engine. For this purpose, tests have been conducted at five different engine speeds (800, 1100, 1400, 1700, 2000 rpm) using blends which are shown as E10, E10EN2, E10EN4 and E10EN6 briefly. The brake torque, brake power, brake specific fuel consumption as performance parameters and CO, CO_2 and NOx as exhaust emissions have been analyzed and all the results have been compared with diesel fuel.

The results are listed below:

- When assessed in terms of performance, diesel fuel has the maximum value of average brake torque and brake power compared with other fuels.
- E10 has the maximum average brake power value than E10EN2, E10EN4 and E10EN6.
- EN addition of 4% is a critical point with respect to brake power. Because brake power have increased with the increasing EN content in fuel from 2% to 4%. After E10EN4, the behavior of brake power with increasing EN content has changed in the opposite direction. This relation between EN content and brake power is also valid for brake torque.
- By the addition of EN, cetane number has increased by about 5.45%, 10.89%, and 16.34% for E10EN2, E10EN4 and E10EN6 respectively compared to the E10 whereas EN has caused a slight decrease in kinematic viscosity, lower heating value and a slight increase in density.
- The highest values of NOx, CO, CO_2 emissions have also been obtained for diesel fuel.
- It is also deduced that EN addition has a reducing effect on NOx, CO emissions and brake power while it has an increasing effect on CO_2 emission and brake specific fuel consumption.

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