Investigations on the Utilization of Ethanol-Unleaded Gasoline Blends on SI Engine Performance and Exhaust Gas Emission

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Abstract-- Due to depletion of conventional fuels and an increase in exhaust emissions at an alarming rate, it is essential to develop an engine which can work on non-conventional fuels and reduce emissions to a greater extent. The present study aims to explore the effects of using ethanol-unleaded gasoline fuel blends on engine performance and exhaust gas emissions in a spark ignition engine. A four-stroke, single cylinder German CT 300 VCR SI engine was used for conducting this study. The ethanol was blended with unleaded gasoline with different percentages of fuel at full throttle opening position and variable engine speed ranging from 1100 - 2000 rpm with an increment of 300 rpm. The engine performance and exhaust gas emissions were evaluated at various engine operating conditions using an engine dynamometer setup. The results showed that blending of unleaded gasoline with ethanol increases the brake torque, brake power, brake mean effective pressure, volumetric and brake thermal efficiencies and reduce the brake specific fuel consumption. Also the results showed that when ethanol is added, the carbon monoxide (CO) and carbon dioxide (CO₂) emission concentrations in the engine exhaust decrease, while the nitric oxide (NO) concentration increases. The oxygen (O₂) concentration also shows an increasing trend with ethanol substitution. The maximum percentage of ethanol substitution was 15%.

Index Term-- SI Engine, Oxygenated Fuel, Engine Performance and Emissions

NOTATIONS
VCR Variable Compression Ratio
Ar Argon
E0 Zero percent ethanol (Pure Gasoline)
E15 15 percent ethanol
H Nascent hydrogen
H₂ Hydrogen
N₂ Nitrogen
PPM Parts per million
RPM Revolutions per minute
SI Spark ignition
UBHC Unburnt Hydrocarbon
OH Oxides of Hydrogen
H₂O Water vapor
N Nascent nitrogen
O Nascent Oxygen
WOT Wide Open Throttle

1. INTRODUCTION
Fuel additives are very important, since many of these additives can be added to fuel in order to improve its efficiency and its performance. One of the most important additives to improve fuel performance is oxygenates (oxygen containing organic compounds). Several oxygenates have been used as fuel additives, such as methanol, ethanol, tertiary butyl alcohol and methyl tertiary butyl ether. Alcohols, like ethanol can be produced by leavening of biomass crops, like sugarcane, wheat and wood. The most positive properties of ethanol include its ability to be produced from renewable energy sources, its high octane number, and its high laminar flame speed. The negative aspects include its low heating value compared to gasoline, and it causes corrosion in the metal and rubber parts of an engine. The engine power improves with ethanol as it has better anti-knock characteristics qualities, which improves engine power with an increase in compression ratio. Ethanol has high latent heat of vaporization. The latent heat cools the intake air and hence increases the density and volumetric efficiency. However, the oxygen available in ethanol composition reduces the heating value more than gasoline does. It is for sure that ethanol can be used as a fuel in spark ignition engines. Many researches have been focused on studying the effects of engine operating conditions and the various fuels used on engine performance and exhaust gas emissions in spark ignition engines. The techniques that are used to eliminate the exhaust gas emissions from spark ignition engines have some influence on engine performance. An overview of techniques is given by Ibrahim Nazzal [1]. He studied the effects of alcohol blends on the performance of a spark ignition engine. For carbureted single cylinder, Maher et al. [2] have studied the effect of ethanol addition to gasoline on engine performance, exhaust gas emissions and noise level at various engine loads. Balaji et al. [3] studied the effects of using ethanol - unleaded gasoline blend on spark ignition engine performance and exhaust gas emission. Farayedhi et al. [4] examined the effects of using oxygenates as a replacement of lead additives in gasoline on performance of a typical spark ignition engine. Studies [5, 6] have shown the analysis of fuel air Otto cycle for iso-octane (C₈H₁₈) and ethanol (C₂H₅OH) by including twelve combustion products i.e. CO₂, H₂O, O₂, N₂, Ar, CO, H₂, O, OH, H, NO and N. The general perception is that alcohol - gasoline blended fuels can effectively lower the emissions and
enhance the engine performance without major modifications to the engine design. Alcohols are an important category of bio-fuels. Ethanol is produced by sugarcane and starch by fermentation. The biomass industry can produce additional ethanol by fermenting some agricultural by-products [7]. Methanol can be produced from coal, biomass or even natural gas with acceptable energy cost. Also gasification of biomass can lead to methanol mixed alcohols and Fischer- Tropsch liquids [8]. Lignocellulosic biomass is a potential source for ethanol that is not directly linked to food production [9]. Shapouri et al. [10] showed that the net energy value of corn ethanol has become positive in recent years due to technological advances in ethanol conversion and increased efficiency in farm production. Corn ethanol is energy efficient, as indicated by energy ratio of 1.24, that is, for every btu (British thermal unit) dedicated to producing ethanol, there is a 24-percent energy gain. Goldenberg et al. [11] demonstrated through the Brazilian experience with ethanol that, economy of scale and technological advances led to increased competitiveness of renewable alternatives, reducing the gap with conventional fossil fuels. Consequently alcohols are particularly attractive as alternative fuels because they are a renewable bio-based resource and oxygenated, thereby providing the potential to reduce particular emissions in spark ignition engines. Kim and Dale [12] estimated that the potential for ethanol production is equivalent to about 32% of the total gasoline production worldwide, when used in E85 (85% ethanol in gasoline) for a mid-size passenger vehicle. Winnington and Siddiqui [13] studied the effect of using ethanol gasoline blends as a fuel on the performance of a Ricardo spark ignition engine for a compression ratio of 8:1 and 10:1. El-Kassaby [14] investigated the effects of ethanol and gasoline blends on spark ignition engine performance. The performance tests showed power improvement with ethanol additive. The maximum improvement was observed at 10% ethanol and 90% gasoline fuel blend. Abdel-Rahman and Osman [15] carried out performance tests using up to 40% of ethanol in gasoline fuel under variable compression ratio conditions. The results showed power improvement with the percentage addition of the ethanol in the fuel blend. The maximum improvement occurred at 10% ethanol and 90% gasoline fuel blend. Yaqoub et al. [16] quantified the performance and exhaust gas emissions for an engine optimized to operate on C1-C5 alcohol/gasoline blends with matched oxygen content. The performance and exhaust gas emissions characteristics of the blends were quantified by using a single-cylinder spark ignition engine. Lower alcohols (C1, C2 and C3)/gasoline blends showed a wider range of operation relative to neat gasoline. Ethanol/gasoline blend showed the highest knock resistance improvement among all tested blends. On the other hand, higher alcohol (C4 and C5)/gasoline blends showed degraded knock resistance when compared with neat gasoline. Al-Hasan [17] showed that blending unleaded gasoline with ethanol increased the brake power, torque, volumetric and brake thermal efficiencies and fuel consumption, while it decreased the brake specific fuel consumption and equivalence air-fuel ratio. Wu et al. [18] tested ethanol/gasoline blended fuel in a conventional engine under various air-fuel equivalence ratios for its performance and emissions. When air-fuel ratio is slightly smaller than one, maximum torque output and minimum brake specific heat consumption are achieved. Yucesu et al. [19] examined the effect of compression ratio on engine performance and exhaust emissions at stoichiometric air/fuel ratio, full load and minimum advanced timing for the best torque in a single cylinder, four stroke, with variable compression ratio spark ignition engine. The engine torque increased with increasing compression ratio up to 11:1, the increasing ratio was about 8% when compared with 8:1 compression ratio. The highest increasing ratio of engine torque was obtained at 13:1 compression ratio with E40 and E60 fuels, the increment was about 14% compared with 8:1 compression ratio. Minimum brake specific fuel consumption was obtained at 11:1 compression ratio with E0 fuel. A comparison with 8:1 compression ratio showed that the bsfc decreased 10% and after 11:1 compression ratio then it increased again. The maximum decrease in it was found to be 15% when E40 was used. Liu et al. [20] also showed that the engine power and torque will decrease when increasing the fraction of methanol in the fuel blends under wide open throttle conditions. However, if spark timing is advanced, the engine power and torque can be improved under WOT conditions. Engine thermal energy is thus improved in almost all operating conditions. Koc et al. [21] investigated the effects of unleaded gasoline and unleaded gasoline/ethanol blends (E50 and E85) on engine performance in a single cylinder four stroke SI engine at two compression ratios (10:1 and 11:1). The engine speed was changed from 1500 rpm to 5000 rpm. at WOT. The results of engine test showed that the ethanol addition to unleaded gasoline increased the engine torque, power and fuel consumption. It was also found that ethanol/gasoline blends allow increasing compression ratios without knock occurrence. Yucesu et al. [22] proposed a new approach based on artificial neural network (ANN) to determine the engine torque and brake specific fuel consumption. Ethanol/unleaded gasoline blends (E10, E20, E40 and E60) were tested in a single cylinder, four stroke cycle SI Engine. The tests were performed by varying the ignition timing, relative air fuel ratio (RAFR) and compression ratio at a constant speed of 2000 rpm with a WOT. The engine torque of ethanol blended fuel was higher than that of E0 obtained at richer working region than stoichiometric air-fuel ratio especially at 10:1 compression ratio. The bsfc increased in proportion to the ethanol percentage. Najafi et al. [23] proposed the use of ANN to determine the engine power, torque, bsfc, brake thermal efficiency, volumetric efficiency and emission components based on different gasoline/ethanol blends and speeds. Experimental data demonstrated that the use of ethanol/gasoline blended fuels will marginally increase brake power and decrease the bsfc. It was also found that the brake thermal efficiency and volumetric efficiency tend to increase when ethanol/gasoline blends are used. Rajan and Saniee [24] investigated the characteristics of hydrated ethanol with...
gasoline as a means of reducing the cost of ethanol/gasoline blends for use as SI Engine fuel. Engine experiments indicate that, at normal ambient temperature, a water/ethanol/gasoline blend containing up to 6 vol% of water in the ethanol constitute a desirable motor fuel with power characteristics similar to those of the base gasoline. As a means of reducing the smog causing components of the exhaust gases, such as the oxides of nitrogen and the unburnt hydrocarbons, the water/ethanol/gasoline blend is superior to the base gasoline. Bata et al. [25] tested different blend rates of ethanol gasoline fuels in engines, and found that the ethanol could reduce the CO and UBHC emissions. Taylor et al. [26] used four alcohol fuels to blend with gasoline and concluded that adding ethanol can replace CO, HC and NO emissions. Chao et al. [27] indicated that using ethanol gasoline blended fuels increase the emission of formaldehyde, acetaldehyde and acetone several times than those from gasoline. Gautam et al. [28] investigated the emissions characteristics between higher alcohol/gasoline blends and neat gasoline. It was found that the cycle emissions of CO, CO$_2$ and organic matter hydrocarbon equivalent from the higher alcohol/gasoline blends were very similar to those from neat gasoline and cycle emissions of NOx from the blends were higher than those from neat gasoline. However, for all emissions species considered, the brake specific fuel consumption was significantly lower than for neat gasoline. This was because the blends had greater resistance to knock and allowed higher compression ratios, which increased engine power output. Palmer in his studies [29] investigated that 10% of ethanol addition to gasoline could reduce the concentration of CO up to 30%.

2. Experimental Analysis

This work has been carried out firstly to assess the potential of ethanol supplementation in spark ignition engines and secondly to calculate the exhaust gas emissions by using mathematical model based upon experimental data. The engine was operated on pure gasoline mode in order to generate the base line data such as brake torque, brake power, brake thermal efficiency, brake specific fuel consumption, volumetric efficiency for different engine speeds. Subsequently, the engine was run under blended fuel mode using ethanol as additive fuel with unleaded gasoline to determine the same parameters up to 15 percent ethanol substitution with ignition timing and compression ratio were kept constant.

2.1. Experimental Test Rig

A test rig as shown in figure (1) was developed to run a single cylinder, 4-stroke, 470 cc, and CT 300 variable compression ratio spark ignition engine. The engine was coupled to an electrical dynamometer, which is equipped with an instrument cabinet (column mounted) fitted with a torque gauge, electric tachometer and switches for the load remote control.

Electrical dynamometer thus allows the trouble-free starting as well as towage. In conjunction with a regenerative feedback unit, this also allows extremely economical operation by feeding the braking power back into electrical network. A Kistler company piezo electric pressure transducer was used to measure the cylinder pressure. Fuel consumption was measured by using a calibrated burette and a stopwatch with an accuracy of 0.2s.

The ethanol was blended with unleaded gasoline to get 10 test blends ranging from 0% to 15% ethanol with an increment of 5%. The fuel blends were prepared just before starting the experiment to ensure that the fuel mixture is homogenous and to prevent the reaction of ethanol with water vapor.

**Procedures**

The engine was started and allowed to warm up for a period of about 30 min. The air–fuel ratio was adjusted to achieve maximum power on unleaded gasoline. Engine tests were performed at 1100, 1400, 1700 and 2000 rpm engine speed at full throttle opening position. The required engine load was obtained through proper dynamometer control. Before running the engine to a new fuel blend, it was allowed to run for sufficient time to consume the remaining fuel from the previous experiment. The operating conditions were fixed and the parameters were continuously measured and recorded. For each experiment, three runs were performed to obtain an average value of the experimental data. The variables that were continuously measured include engine rotational speed (rpm), torque, time required to consume 90 cc of fuel blend (s), and air–fuel ratio. The parameters, such as fuel consumption, air consumption, equivalence air–fuel ratio, volumetric efficiency, brake power, brake mean effective pressure, brake specific fuel consumption, brake thermal efficiency, stoichiometric air–fuel ratio and lower heating value (LHV) of the fuel blends, were determined by using the standard equations. The experimental engine is water–cooled, carbureted SI engine made up of grey cast - iron. Table I lists the important engine specifications.

![Fig. 1. The schematic line diagram of experimental set up.](image-url)
results at the same operating conditions related to the experimentally generated data. The model takes as input the following known data:

(a) engine geometry,
(b) operating conditions (ignition timing, air fuel ratio, engine speed),
(c) ambient conditions (temperature and pressure), and
(d) fuel composition at inlet valve closer.

4.1 Combustion of Fuels: assuming No Dissociation

The composition of air [31] is considered to be 20.95% oxygen, 78.09% nitrogen and 0.93% argon by volume, which leads to the conclusion that for each mole of oxygen 3.727 moles of nitrogen and 0.05 moles of argon are involved. Therefore, the complete basic combustion equation of iso-octane and ethyl alcohol can be written as:

\[ C_{8}H_{18} + 12.5(O_{2} + 3.727N_{2} + 0.05Ar) \rightarrow 8CO_{2} + 9H_{2}O + 46.587N_{2} + 0.625Ar \]

\[ C_{2}H_{5}OH + 3.0(O_{2} + 3.727N_{2} + 0.05Ar) \rightarrow 2CO_{2} + 3H_{2}O + 11.181N_{2} + 0.15Ar \]

Here the stoichiometric or chemically correct amount of air has been used; this is the exact amount of air needed for completely oxidized products. The relative amount of air-fuel taking part in the reaction is called as air-fuel ratio.

4.2 Combustion of Fuels with Dissociation

The maximum temperature attained in combustion process is appreciably lower than those based upon complete combustion because of the heat loss and dissociation of the products of combustion. Appreciable dissociation occurs at high temperatures, and is accompanied by absorption of internal energy, which is transformed into chemical energy. Thus the dissociation products will have chemical energy associated with them. Hydrocarbon fuels burn to carbon dioxide and water, which appears in the products along with nitrogen and argon when air is used as the oxidizing agent. Dissociation results in the formation of appreciable quantities of CO, H₂ and O₂ according to the reversible reactions.

\[ 2CO_{2} \rightarrow 2CO + O_{2} \]
\[ 2H_{2}O \rightarrow 2H_{2} + O_{2} \]

Other constituents, such as N, O, H, OH, NO, and C may be formed by further dissociation and the combustion of the various constituents. Both combination of the various constituents into products of combustion and dissociation of the products are assumed to occur simultaneously in various parts of the mixture at chemical equilibrium conditions. At equilibrium the effect of the energy involved in primary reaction is equal to the effects of the energy in the secondary reaction.

5. RESULTS AND DISCUSSIONS

Ethanol contains an oxygen atom in its basic form; it therefore can be treated as a partially oxidized hydrocarbon. When ethanol is added to the blended fuel, it can provide more
oxygen for the combustion process and leads to the so-called “leaning effect”. Owing to the leaning effect, CO emission will decrease tremendously, although the engine power slightly increases. The influence of using the ethanol additive to pure gasoline is clearly obvious on engine performance and exhaust gas emissions.

Figure 2 depicts the variation of brake power with respect to ethanol concentrations for different engine speeds. The brake power of the engine increases with an increase in engine speed for all fuel blends. However, due to better combustion conditions and lower temperature in the intake manifold, the engine power increases when the ethanol is added. The figures show that the brake power increases by 11.06%, 9.19% and 1.35% with fuel blend 15% ethanol - 85% gasoline, 10% ethanol - 90% gasoline and 5% ethanol - 95% gasoline respectively compared to pure gasoline for the engine speed of 2000 rpm. Generally ethanol will ignite faster than gasoline; therefore an engine burning ethanol would produce more power. It is also possible to take the advantage of the higher octane rating for ethanol. This would increase the efficiency of converting the potential combustion energy into power.

Figure 3 shows that the brake thermal efficiency increases as the engine speed increases and reaches a maximum at speed of 1700 rpm and then it decreases with an increase in engine speed for all fuel blends except pure gasoline, where the effect of mechanical loss has been more significant. Also, it is observed that the brake thermal efficiency increases by 18.16%, 14.61% and 11.31% with 15%, 10% and 5% ethanol-gasoline blends respectively compared to pure gasoline. Generally the addition of ethanol shows higher brake thermal efficiency compared to gasoline and this would provide more engine brake power within fuel consumed.

In figure 4, the brake specific fuel consumption decreases as the engine speed increases and reaches a minimum at engine speed of 1700 rpm and then it increases with an increase in engine speed for all fuel blends except pure gasoline. It was found that the brake specific fuel consumption also decreases by 15.07%, 12.56% and 10.56% with 15%, 10% and 5% ethanol-gasoline blends respectively compared to pure gasoline. Because of oxygen content available in ethanol, the blend causes better combustion compared to pure gasoline and causes enhanced power output.

Figure 5 shows the trend of brake mean effective pressure with respect to ethanol concentrations at different engine speeds. There is a direct relationship between brake mean effective pressure and brake torque. The torque curve with engine speed is identical to the brake mean effective pressure.
The brake mean effective pressure increases as the engine speed increases and reaches a maximum at speed of 1700 rpm and then it decreases with an increase in engine speed for all fuel blends. It was found that the brake mean effective pressure also increases by 11.99 %, 9.25 % and 3.32 % with fuels 15% ethanol - 85% gasoline, 10% ethanol - 90% gasoline and 5% ethanol - 95% gasoline respectively. The addition of ethanol shows higher brake mean effective pressure compared to gasoline because of the same reason as explained in fig. 4.

In Figure 6 the variation of volumetric efficiency with respect to ethanol concentrations at different engine speeds can be examined. The volumetric efficiency decreases as the engine speed increases for all fuel blends due to frictional loss. Also, the figures showed that the volumetric efficiency increases by 1.54%, 1.24% and 1.12% with 10% ethanol – 90% gasoline, 15% ethanol – 85% gasoline and 5% ethanol - 95% gasoline respectively compared to pure gasoline for the engine speed. The ethanol blends show higher volumetric efficiency compared to pure gasoline because of more oxygen availability inside the engine cylinder.

Figure 7 highlights the variation of exhaust gas temperature with respect to ethanol concentrations. The exhaust gas temperature increases throughout with an increase in engine speed for all fuel blends because more fuel will be burnt inside the cylinder. However, due to better combustion characteristics, the exhaust gas temperature increases when ethanol is added. The figures showed that the exhaust gas temperature increases by 4.03%, 3.42% and 1.73% with fuels 10% ethanol - 90% gasoline, 15% ethanol - 85% gasoline and 5% ethanol - 95% gasoline respectively compared to pure gasoline for the engine speed of 2000 rpm.
Figure 12 shows the variation of maximum cylinder pressure with respect to crank angle for two different fuel concentrations (E0 and E5). The maximum cylinder pressure occurs at the combustion stroke, and this process is the most important process because the pressure of the hot burned gases inside the engine cylinder pushes the piston downward to produce engine power. For all engine speeds, the 5 percent ethanol (E5) blend has slightly higher cylinder pressure than pure gasoline which means the better combustion process. Also it was found that the maximum cylinder pressure was observed at 1700 rpm, and it increases by 1.95 % with the fuels 5% ethanol - 95% gasoline compared to pure gasoline.

The simulated results for exhaust gas emissions for CO, CO2, NO and O2 have been shown in Figures 13 –16 with respect to pure gasoline and ethanol concentrations (5, 10 and 15%). Ethanol addition up to 15% to unleaded gasoline has two major effects. It decreases the concentrations of carbon monoxide and carbon dioxide. The nitric oxide and oxygen concentration show an increasing trend. The figures show that the 15 percent ethanol addition to unleaded gasoline reduces the concentration of CO by about 65 % and the concentration of CO2 by about 60.89 % for 15 percent ethanol substitution compared to pure gasoline and this is due to the reduction in carbon atoms concentration in the blended fuel and the high molecular diffusivity and high flammability limits which improves mixing process and hence combustion efficiency. Generally above 15% ethanol substitution, this effect can be seen more clearly [17, 18]. Increase in CO2 can be seen after 15% ethanol blend. Little variation does exist in simulated results. O2 concentration shows an increasing trend as ethanol is an oxygenate fuel, it releases oxygen while burning.
6. CONCLUSIONS

The main conclusions deduced from these investigations are as follows:

The engine performance and pollutant emissions of a SI engine have been investigated by adding a maximum value of 15% ethanol– 85% gasoline blend over pure gasoline. The basic aim of this study was to substitute only up to 15% ethanol in unleaded gasoline in a small engine, with an idea to apply this investigation in engines of smaller size.

Engine performance has increased with using ethanol additive to gasoline, where the maximum increment in brake power, brake thermal efficiency, volumetric efficiency, brake torque and brake mean effective pressure were found to be higher than pure gasoline by about 11.06 %, 18.16 %, 1.54 %, 11.99 % and 11.99 % respectively. Also it was found that a decrement in brake specific fuel consumption was about 15.07 %. Combustion processes inside the cylinder is better with ethanol blend with gasoline, where the maximum cylinder pressure during combustion stroke was found to be higher than pure gasoline by about 1.95 %.

Exhaust gas emissions are lower by using ethanol-gasoline blends, where the maximum reduction in emissions was found to be 65 % and 60.89 for CO and CO2 respectively over pure gasoline, while the NO emission was found to be higher than pure gasoline. Usually CO concentration decreases due to leaning effect with ethanol addition and CO2 shows increasing trends after 15% due to better combustion with ethanol blends. Usually the 15 percent ethanol blend was found to be the beneficial substitution that achieves satisfactory engine performance and exhaust gas emissions.

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REFERENCES


