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# The Performance and Emission Characteristics of SI Engine Running on Different Ethanol-Gasoline Blends

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**Abstract**—This paper presents a review of the use of ethanol in SI engine, its performance and emission characteristics based on the works of different researchers and scientist available in the literature. The advantages of using ethanol as SI engine fuel include its greenness, renewability, higher availability and usability in near future, higher octane number, higher volumetric efficiency, higher compression ratio and biodegradability. Ethanol can be produced biologically from sugarcane, crop residues, cellulose, agricultural biomass, municipal waste etc. The experiment conducted by different researchers and their experimental results shows that brake specific fuel consumption, brake torque, indicated power, thermal efficiency increases or decreases depending upon the operating condition of the engine and ethanol percentage in the ethanol-gasoline blends. However, the compression ratio always increases due to enhancement of the octane number of the blend. On the other hand volumetric efficiency increases with the increase in ethanol percentage in the blends. Also there is a significant reduction in the emission of unburned hydrocarbon and carbon monoxide with ethanol and ethanol gasoline blend. But the $CO_2$ emission is more with ethanol and $NO_x$ emission increases or decreases depending upon the engine operating conditions.

**Index Terms**— ethanol, gasoline, blend, SI engine, efficiency, BSFC, emission.

## 1 Introduction

The rapid industrialization and motorization of the world has led to a steep rise for the demand of petroleum based fuels. As a result, the reserves of the fossil fuel are rapidly exhausting. Sheehan et al. [1] estimated known petroleum reserves to be depleted in less than 50 years at the present rate of consumption. So there is a great anxiety about the shortage of energy because of finite reserves of the fossil fuel. Besides designing more efficient engines, we need to search for the substitute of the fuels we are using at present, to fulfill our future needs. Furthermore, environmental protection issues have been emphasized all over the world in recent years, so it is urgent to find some clean and renewable fuel for spark ignition (SI) engines [2]. Ethanol is considered to be one of the most promising alternative renewable fuels. Ethanol can be fermented and distilled from sugarcane and grain, cellulosic materials such as wood, agricultural solid wastes, coal, sweet sorghum etc. and also it has potential to reduce CO, HC, $NO_x$, and particulates emissions. Ethanol has some advantages over gasoline, such as high octane number and flame speed, high latent heat of vaporization thereby higher volumetric efficiency.

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It contains 35% oxygen that helps in complete combustion of fuel and thus reduces harmful tailpipe emissions. Although having these advantages, due to limitation in technology, economic and regional considerations ethanol as a fuel still is not used extensively.

Under the environmental consideration, using ethanol gasoline blend is better than use of pure gasoline because of the renewability and less toxicity of ethanol. Several studies on the performance and emission characteristics of spark ignition engines, fuelled with pure gasoline and blended with ethanol, have been performed and are reported in the literature. In this paper, the performance and emission characteristics of SI engine using ethanol and different blends of ethanol-gasoline as fuel have been presented from the various studies conducted by different researchers to have been an overview of the present status of ethanol- gasoline blends application as a substitute fuel to conventional gasoline.

## 2 Present Status Of ethanol As Motor Fuel

### 2.1 World wide ethanol Development

Worldwide ethanol production for transport fuel raised between the years 2000 to 2007 from 17 billion to more than 52 billion liters. From 2007 to 2008, the share of ethanol in global gasoline type fuel use increased from 3.7% to 5.4% [3]. In 2009, worldwide ethanol fuel production reached 19.5 billion gallons (73.9 billion liters) [4]. It is forecasted that the global use of ethanol will increase 25 times by 2020.

Brazil has the largest and most successful bio-fuel programs in the world, involving production of ethanol fuel from sugarcane, and it is considered to have the world's first sustainable bio-fuels economy [5]. In 2006 Brazilian ethanol provided 18%

of the country's road transport sector fuel consumption needs [6], and by April 2008, more than 50% of fuel consumption for the gasoline market [7].

Together, Brazil and United States lead the industrial world in global ethanol fuel production, accounting together for 89% of worldwide production [8]. In 2009 Brazil produced 24.9 billion liters (6.57 billion U.S. liquid gallons) [8], representing 33.7% of the world's total ethanol used as fuel. Sugar cane plantations cover 3.6 million hectares of land for ethanol production, representing just 1% of Brazil's arable land, with a productivity of 7,500 liters of ethanol per hectare, as compared with the U.S. maize ethanol productivity of 3,000 liters per hectare [9].

The consumption of bio-ethanol is largest in Europe in Germany, Sweden, France and Spain. Europe produces equivalent to 90% of its consumption (2006). Germany produced 70% of its consumption, Spain 60% and Sweden 50% (2006). In Sweden there are 792 E85 filling stations and in France 131 E85 service stations with 550 more under construction. The production of ethanol throughout the world has been given in the table 1.

### 2.2 Ethanol: Indian Context

India depends heavily on imported petroleum oil to meet her transportation fuel need. While the indigenous production of crude oil has increased almost five times during the last three decades, the import has increased by a factor of nine during the same span, signifying a rapidly increasing gap between demand and indigenous production. Given this wide gap in demand and indigenous production of crude oil and the increasing cost of imported oil, ethanol is seen as a techno-economically feasible alternative to petroleum oil in transportation.

TABLE 1

WORLDWIDE ETHANOL PRODUCTION

| World Rank | Country/Region | Millions of U.S. Gallons per Year | | |
|---|---|---|---|---|
| | | **2009** | **2008** | **2007** |
| 1. | United States | 10,750.00 | 9,000.00 | 6,498.60 |
| 2. | Brazil | 6,577.89 | 6,472.20 | 5,019.20 |
| 3. | European Union | 1,039.52 | 733.60 | 570.30 |
| 4. | China | 541.55 | 501.90 | 486.00 |
| 5. | Thailand | 435.20 | 89.80 | 79.20 |
| 6. | Canada | 290.59 | 237.70 | 211.30 |
| 7. | India | 91.67 | 66.00 | 52.80 |
| 8. | Colombia | 83.21 | 79.30 | 74.90 |
| 9. | Australia | 56.80 | 26.40 | 26.40 |
| 10. | Others | 247.27 | _ | _ |
| | World Total | 19,534.99 | 17,335.29 | 13,101.70 |

Blending of ethanol with petrol got momentum in India only in the year 2000 when the Ministry of Petroleum and Natural Gas decided to take up pilot projects at three locations of the major sugar-producing states Maharashtra and Uttar Pradesh to study the related aspects of blending ethanol with petrol and its use.These pilot projects were commissioned at Miraj and Manmad in Maharashtra and at Bareilly in Uttar Pradesh during the year 2001. The Government of India issued a notification on 12$^{th}$ September, 2002 mandating supply of 5% ethanol-blended petrol in nine States - Andhra Pradesh, Goa, Gujarat, Haryana, Karnataka, Maharashtra, Punjab, Tamil Nadu and Uttar Pradesh, and four Union Territories - Chandigarh, Dadra & Nagar Haveli, Daman & Diu and Pondicherry with effect from 1$^{st}$ January, 2003. As per the notification, in Andhra Pradesh the project was commissioned in Visakhapatnam. As the current total consumption of gasoline in these 9 States and 4 Union Territories amounted to about 4.6 MT per year, the requirement of ethanol at a 5% blend ratio works out to around 320-350 million liters.

## 3 PROPERTIES OF ETHANOL

Properties of any fuel depend fully on its chemical compositions which determine the performance and emission characteristics of the engine. Ethanol is an oxygen enriched chemical agent; containing 35% oxygen by weight. It therefore can be treated as partially oxidized fuel [10]. When ethanol is added to the blended fuel (gasoline) it can provide more oxygen for the combustion process and leads to the so-called "leaning effect". Owing to the leaning effect engine combustion is improved. Lower heating value (LHV) has an average value of 26.8 MJ/Kg and the stoichiometric air to fuel ratio has a typical value of 9.0. In comparison with commercial gasoline, ethanol has higher density and octane number. In addition the high flash point (more than 56°C) of ethanol makes the storage and transportation issues less important Ethanol has higher octane number than gasoline, thus it can lead in operation at higher compression ratios therefore, improvement in power output, efficiency and fuel consumption. Different properties of ethanol are compiled from the previous works [11, 12] and presented in the tabular form for ready reference in table 2.

## 4 PERFROMANCE CHARACTERISTICS OF ETHANOL FUELED SI ENGINE

One of the purposes of this paper is to investigate the performance of SI engine using different percentages of ethanol-gasoline blends as fuel. Ethanol blends are referred to as Exx. The 'xx' indicates the amount of ethanol by volume in the blend of gasoline and ethanol. Ethanol can be used as an SI engine fuel in several forms: low-level blends (e.g. <20% ethanol in gasoline), high-level blends (e.g. >85%) or pure ethanol. Pure ethanol and high level blends may need some engine modifications.

Several studies have been done on the performance of the SI engine using different percentages of ethanol in ethanol-gasoline blends. Palmer [13] for instance, used various blend rates of ethanol-gasoline fuels in engine tests. The results indi-

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cated that 10% ethanol addition increases the engine power by 5% and the octane number can be increased by 5%. Al-Hasan [14] investigated the effect of ethanol-unleaded gasoline blends on performance and emission. The unleaded gasoline was blended with ethanol to prepare 10

TABLE 2

PROPERTIES OF ETHANOL AND GASOLINE

| Fuel Property | Ethanol | Gasoline |
|---|---|---|
| Formula | $C_2H_5OH$ | $C_4$ to $C_{12}$ |
| Molecular weight | 46.07 | 100-105 |
| Density, kg/l, 15/15 °C | 0.79 | 0.69-0.79 |
| Specific gravity (Relative density), 15/15 °C | 106 –110 | 91 |
| Freezing point, °C | –114 | –40 |
| Boiling point, °C | 78 | 27-225 |
| Vapor pressure, kPa at 38 °C | 15.9 | 48-103 |
| Specific heat, kJ/kg K | 2.4 | 2 |
| Viscosity, mPa s at 20 °C | 1.19 | 0.37–0.44 |
| Flash point, °C | 13 | –43 |
| Auto-ignition temperature, °C | 423 | 257 |
| Latent heat of vaporization, (kJ/kg) | 923 | 380–500 |
| Lower heating value, (MJ/kg) | 26.8 | 42.7 |
| Flammability limits, Vol% | | |
| Lower | 4.3 | 1.4 |
| Higher | 19 | 7.6 |
| Stoichiometric air-fuel ratio, weight | 9 | 14.7 |
| Octane number | | |
| Research (R) | 108.6 | 88–100 |
| Motor (M) | 89.7 | 80–90 |
| Antiknock Index (R+M)/2 | 99.1 | 84–95 |

Source: Yuksel and Yuksel [11], Koc et al. [12]

test blends ranging from 0% to 25% ethanol with an increment of 2.5%. Ethanol addition resulted in an increase in brake power; brake thermal efficiency, volumetric efficiency and fuel consumption by about 8.3%, 9%, 7% and 5.7% mean average values, respectively. The best performance and emissions results were obtained for 20% ethanol. Al-Kassaby [15] studied the effect of ethanol-gasoline blends on SI engine performance. The performance tests were conducted using different percentage of ethanol-gasoline up to 40% under variable compression ratio conditions. The results showed that engine indicated power improved with ethanol addition, the maximum improvement occurring at the 10% ethanol and 90% gasoline fuel blend. Wu et al. [16] investigated the effect of air-fuel ratio on SI engine performance and pollutant emissions using ethanol-gasoline blends. The result of engine performance tests showed that torque output improves when using ethanol-gasoline blends. However, there is no appreciable difference on the brake specific heat consumption. Abdel-Rahman and Osman [17] conducted an experimental investigation on varying the compression ratios of SI engine working under different ethanol-gasoline fuel blends. In their experiment 10%, 20% and 30% ethanol-gasoline blends were used as fuel. Optimum compression ratio which obtained maximum indicated power was determined for each blend. For 10%, 20% and 30% ethanol-gasoline blends, the optimum compression ratios of 8, 10 and 12 were obtained. Under various compression ratios of engine, the optimum blend rate was found to be 10% ethanol with 90% gasoline. Topgul et al. [18] investigated the effect of ethanol-unleaded gasoline blends on performance, emission and ignition timing. The unleaded gasoline was blended with ethanol to prepare E0, E10, E20, E40 and E60 blends. The experiments were performed under variable compression ratio conditions (8:1, 9:1 and 10:1) at a constant speed (2000 rpm) at wide open throttle. At 10:1 compression ratio advancing the ignition timing to 24°CA caused knock occurrence with E0 fuel. However, knock occurrence was not observed up to 36°CA advance ignition timing with unleaded gasoline-ethanol blends (E40 and E60). Fig. 1 shows the variation of brake torque with ignition timing for compression ratio of 10:1. Figure shows that ethanol addition increase brake torque at all ignition timing at the compression ratio of 10:1 than 8:1 and 9:1. It is due to anti-knock property of ethanol i.e. ethanol act as an anti-knock agent in the ethanol-unleaded gasoline blends. Due to its higher octane number compare to gasoline and for that reason they concluded that thermal efficiency of the engine may be improved. Yucesu et al [19] investigated the performance of a variable compression (8:1 to 13:1) SI engine using E0, E10, E20, E40 and E60 as fuels. Fig. The variation of brake specific fuel consumption with compression ratio for different blends of ethanol and gasoline has been shown in Fig. 2. The figure shows BSFC increases with the percentage of ethanol in the blend. The highest improvement of BSFC was obtained with E60 fuel as 14.5% and 17% at 3500 and 5000 rpm engine speeds, respectively.

## 4 EMISSION CHARACTERISTICS OF BIO-ETHANOL FUELED SI EBNGINE

Due to the introduction of stringent emission norms through different international protocols, environmental impacts of any alternative fuel to be used in IC engines should be evaluated first. Most of the emissions from the engines are carcigenous and harmful for environment as well as human health. Only four most important emissions considered under this study are CO, unburned hydrocarbon (HC), $NO_x$ and $CO_2$.

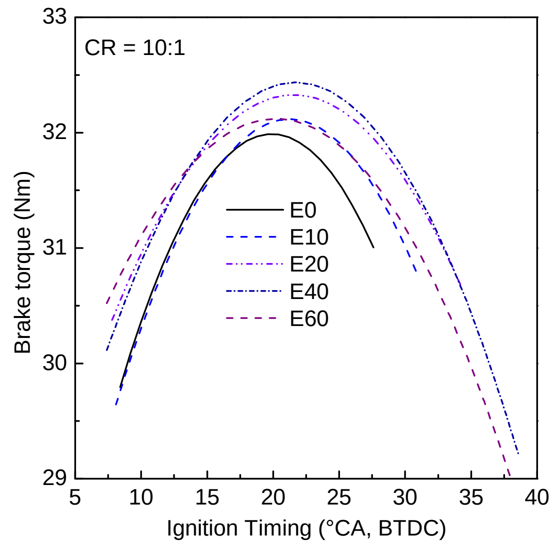


Fig 1. Variation of brake torque with ignition timing for different gasoline-ethanol blend. Source: Topgul et al. [19]

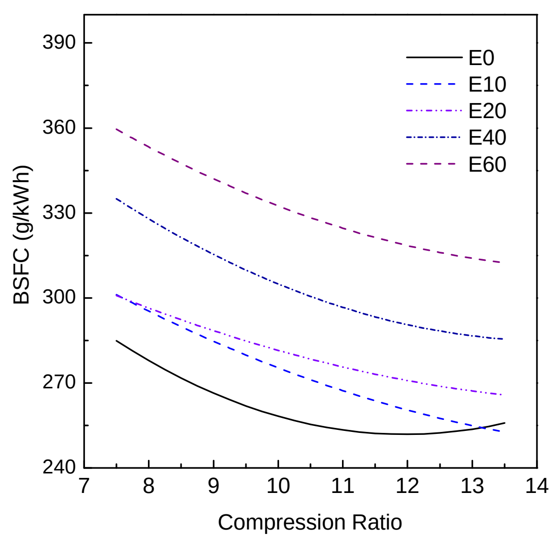


Fig 2. Variation of BSFC with compression ratio for different blends of gasoline and ethanol. Source: Yucesu et al. [19]

### 4.1 Effect of Ethanol on CO Emissions

Many studies have shown that the oxygen in ethanol leads to a significant reduction in mobile carbon monoxide (CO) emissions. But the levels of reduction reported by different researchers are not the same. Charalampos et al. [20] investigated the behavior of a small four-stroke engine when mixtures of ethanol-gasoline and methanol-gasoline were used as fuel. In the engine test, 11 test blends ranging from 0% to 100% ethanol with an increment of 10% were used. They have found that the CO emissions were decreased as ethanol content in fuel increased.

In the national fuel laboratory of American EPA, Guerrieri et al. [21] made a test and observed that as ethanol content was increased over 25%, CO emission decreases. Pikunas et al. [22] experimented on influence of composition of ethanol-gasoline blends on parameters of internal combustion engines. They have found that CO emission decreased with the increase of percentage of ethanol in the ethanol gasoline blends. Fig. 3 represents the variation of CO emission with the variation of engine speeds. It was observed by authors that in the beginning, when the engine power and revolutions were little, the amount of CO decreased by 15%, when they used E10 blend in comparison with E0. When the power and revolutions were increased, the difference of CO emission increases by 30%. They concluded that CO emission decreases as a result of the leaning effect caused by the ethanol addition. Topgul et al. [18] showed that 40% addition of ethanol reduced 31.8% CO at 9:1 compression ratio. Hsieh et al. [2] had tested 0%, 5%, 10%, 20%, 30% ethanol of blended fuels in an SI engine. They found that 20% and 30% addition of ethanol CO reduced up to 90% depending on the operation conditions of the engine. They concluded that CO reduction due to leaning effect and improving combustion caused by the ethanol addition. Fig. 4 shows the variation of CO reduction with throttle valve opening. Whitten [23] have shown that CO can be equivalent to 25% to 50% of the mobile- related contribution from volatile organic compounds (VOC). A significant reduction in CO is provided by the high oxygen content of ethanol.

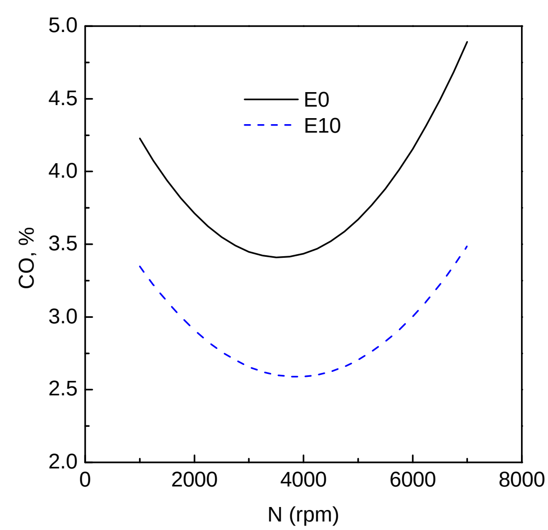


Fig 3. Variation of CO emission with engine speed for E0 and E10 blends. Source: Pikunas et al. [22].

### 4.2 Effect of Ethanol on HC Emissions

The level of unburned hydrocarbon in the exhaust of an internal combustion engines (petrol or diesel) indicates the degree of completeness of fuel combustion. Most of the researchers reported on the basis of their experimental investigations that unburned hydrocarbon emissions decrease to certain extent from the engine when fueling with gasoline- ethanol blends instead of conventional gasoline alone. Hsieh et al. [2] tested on commercial SI engine with 0%, 20%, 40%, 60%, 80% and 100% ethanol in the blends at wide open throttle condition. In their experimental results they found that HC emission decreases from 20% to 80%. And they pointed out that equivalent ratio increases with the increment of percentage of ethanol and for this reason complete combustion take place thereby reduced HC emission. The experimental results of Celik [24] showed that the value of HC emission from E25 and E50 fuels are 271 ppm and 245 ppm respectively and 331 ppm for E0 i.e. conventional gasoline but with E75 and E100 fuels HC rises to 340 ppm to 483 ppm respectively. Yucesu et al. [19] have conducted an experiment with various ethanol-gasoline blends on variable compression SI engine and analyzed their results. They have observed that HC emission decreases up to 16.45% by using E60 at 5000 rpm engine speed. Koc et al. [12] investigated the effect of using unleaded ethanol-gasoline with E0, E50, E85 blends on variable compression SI engine performance and exhaust emissions. In their experiment they pointed out that the HC emission decreases with the increase in ethanol addition comparing with gasoline alone and the maximum reduction of HC emission was obtained with E85 fuel. The results from the experimental work of Koc et al. [12] have been presented Fig. 5 and it shows the variation of HC emission with respect to engine speed at a compression ratio of 10:1. A significant reduction in HC emission was observed between 1500 and 5000 rpm speeds at both compression ratios as a result of the leaning effect and oxygen enrichment caused by the ethanol addition. Also, the HC emission decreases with the increase of engine speed in general. Furthermore, the air-fuel mixing process improves as the turbulence intensity increases at the higher engine speeds. These provide more complete combustion and reduction in HC emissions.

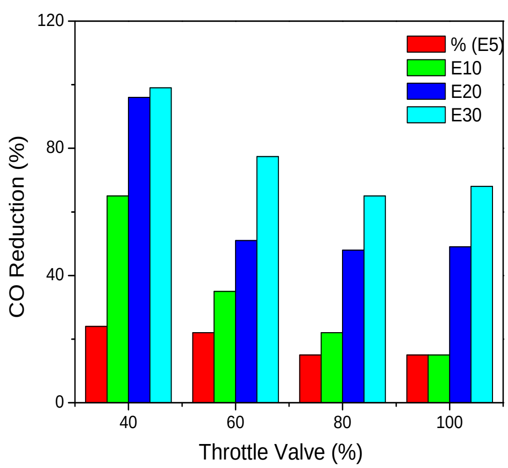


Fig 4. Variation of CO reduction with throttle position for different blends of gasoline and ethanol. Source: Hsieh et al. [2]

### 4.3 Effect of Ethanol on $CO_2$ and NOx Emissions

Most of the studies found in the literature show a slight increase of $NO_x$ emission but $CO_2$ emission increases to some extent in the exhaust of the engine when ethanol and its blends with conventional gasoline are used as fuels. Some researchers reported that $NO_x$ emission depends on certain operating conditions. $CO_2$ emission increases due to improvement of the combustion and this improvement due to oxygen richness of the ethanol fuel.

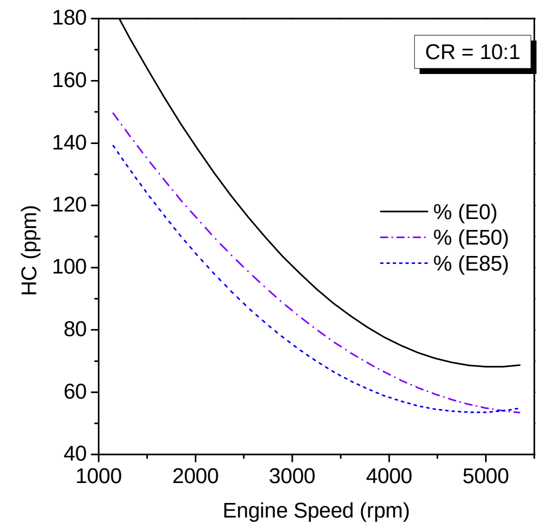


Fig 5. Variation of HC emission with engine speed for different gasoline ethanol blends. Source: Koc et al. [12]

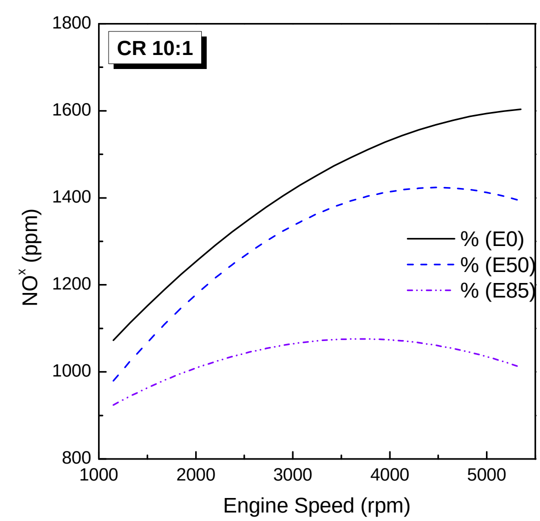


Fig 6. Variation of NOx emission with engine speed for different gasoline ethanol blends. Source: Koc et al. [12]

Pikunas et al. [22] have shown experimentally that $CO_2$ emission increases due to increasing the amount of ethanol in the fuel mixture and for this reason better combustion take place and the amount of incomplete combustion product decreases. In their study they found that $CO_2$ emission increased by 5-10% depending on engine operating conditions. Yuksel and Yuksel [11] tested 60% ethanol and 40% gasoline on 4-cylinder

Figure 6. Variation of $NO_x$ emission with engine speed for different gasoline ethanol blends. Source: Koc et

SI engine by the modification of the carburetor with varies of 25%, 50%, 75% and 100% throttle valve opening. From there experimental result it has seen that $CO_2$ emission increases by 20% and $NO_x$ emission decreases under some operating conditions. Koc et al. [12] in their experiment study pointed out that nitric oxide levels mainly depend on the peak temperatures achieved during combustion. They observed that $NO_x$ emissions are formed above temperature of $1500^0$C and $NO_x$ emissions peak at slightly lean mixture (fuel air equivalence ratio greater than one). They concluded that due to higher latent heat of vaporization $NO_x$ emission decreases at 10:1 compression ratio but increases at 11:1 compression ratio due to maximum combustion temperature and higher compression ratio. The effect for compression ratio of 10: 1 has been graphically shown in Fig.6 from the experimental results of Koc et al. [12]. The effect is more pronounced at higher engine speed. The reduction in $NO_x$ emission is about 60% with 85% ethanol blended fuel at 5000 rpm.

## 5 Conclusion

The aim of this review work was to study the performance and emission characteristics of SI engine using ethanol as a fuel blended with gasoline. Different properties of ethanol which are crucial for the assessment of performance and emission characteristics of an engine have been discussed and compared to those of conventional gasoline.

The performance characteristics are improved but only to some extent with the use of ethanol or blends of ethanol and gasoline. The power, torque increases at a certain percentages of ethanol in the blends and BSFC increases with the increment of the percentage of ethanol in the blend. Also octane number and volumetric efficiency increases with the increase in percentage of ethanol in the blends.

Emission characteristic are improved significantly with the use of ethanol blending with gasoline. The review concludes that CO, HC emissions from SI engine are reduced to a large extent when ethanol-gasoline blends is used instead of gasoline alone as a fuel. The maximum reduction in emissions of CO and HC are around 90% and 80%. $CO_2$ emission increases with the increase of ethanol in the blends due to improvement in combustion. $NO_x$ emission may decrease or increase depending upon the operating condition i.e. compression ratios, percentage of ethanol in the blends etc. As it can obtained biologically from crops residue and grass to municipal wastes, so the feedstock areas for ethanol around the world are vast and it may be meet the future needs for SI engine.

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