International Journal of Analytical, Experimental and Finite Element Analysis (IJAEFEA), Issue. 4, Vol. 5, Dec 2018
e-ISSN: 2394-5141, p-ISSN: 2394-5133, pp 50 - 59
DOI: 10.26706/IJAEFEA.4.5.20181201

The Impacts of Ethanol - Gasoline Blended Fuels on the Pollutant Emissions and Performance of a Spark - Ignition Engine: An Empirical Study

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***Abstract*— The blending of ethanol with imported gasoline types has been compulsory since January 1, 2018, with the Communiqué No. 30098 published in the Official Gazette in Turkey. In line with this, it is aimed to determine the effects of gasoline-ethanol blends on engine performance and exhaust emissions resulting from the use of an SI engine. The experiments were performed at different speeds for different ethanol-gasoline blends (E0, E10 and E20) under full load in a four-stroke, single-cylinder engine. As a result, air-fuel mixture ratios, torque, power, vibration and noise values, specific fuel consumption, harmful gas emissions (CO, HC, CO_2 and NOx) was measured. Measurements were obtained with 96% accuracy. In this study, carbon monoxide and hydrocarbon emissions decreased, carbon dioxide and nitrogen oxide emissions increased by the addition of ethanol to gasoline. On the other hand, the addition of ethanol has also led to a certain increase in brake specific fuel consumption, vibration and noise levels.**

Index Terms— Engine performance, Ethanol-gasoline blends, Exhaust emission, Fossil fuels.

I. Introduction

The more studies and developments for the internal combustion engines (ICEs) have gained momentum particularly after the late of the 1800s. Nicolaus Otto, Rudolph Diesel, Gottlieb Daimler, Karl Benz and Henry Ford contributed and gave the direction of the new developments on the automobile world between the years of 1800-1930 and also directly helped to the invention of compression ignition engine (CI) and spark ignition (SI) engine [1]. Even today, their outstanding attempts in vehicular systems still have a vital role and in use. Currently, ICEs have been the foundation for the accomplished achievements for many industrial technologies such as the applications of power generation, military, telecommunication, agriculture, transportation, offshore drilling, marine and generator [2]. On the other hand, the popularity of ICEs and its use in nearly all sectors have caused great energy consumption and undoubtedly played a leading role of the most of the depleting fossil fuel sources [3] because ICEs have been powered by the burning of the fossil fuels and the reserves of the fossil fuels have a finite.

Today, there are nearly 380 million commercial vehicles and 1.2 billion passenger cars across the world. These vehicles and cars have gained the motion as a result of the burning of fossil fuels [4]. It is predicted that fossil fuels will completely run out in near future. That is why we need to find an alternative energy source instead of fossil fuels and decrease our dependency on fossil fuels, immediately. Therefore, it is of great importance that the new energy source to replace fossil fuels is also in equipment with ICEs. Although many alternatives are considered in this context, biomass (bioenergy) for ICEs is the most accepted energy source. In addition, the use of biomass has the ability to be applied directly to the fuel tank without any modification on the vehicle. There are basically two methods for biomass power generation for ICEs. These are biofuels obtained with liquid-biomass and gas-biomass blends. The most preferred biomass for ICEs is ethanol (known as ethyl alcohol, the chemical representation C_2H_5OH) and methanol (known as methyl alcohol, the chemical representation of CH_3OH), respectively. The low thermal values of methanol and ethanol compared to gasoline, the low fuel values of the new fuel formed by the mixing of these alcohol species with the gasoline is also lower than the thermal value of pure gasoline. Therefore, blends of methanol-gasoline [5, 6] and ethanol-gasoline [7, 8] increase specific fuel consumption compared to pure gasoline. However, many studies conducted in the literature have proved that the new mixture causes a great deal of reduction in harmful gas emissions such as CO (carbon monoxide), HC (hydro carbon) and NO (nitrogen oxide). Therefore, the use of biomass in the fuel tank turns fossil fuels into a cleaner form of energy source.

This study mainly focused on experimentally investigation and comparing the motor performance by using various rates of ethanol and gasoline blends. Ethanol is the most popular source of renewable energy for spark ignition engines [9, 10]. On the other hand, ethanol is a pure substance and includes nearly 34.7% by weight of oxygen. Hence, the stoichiometric air-fuel ratio of ethanol is 9 and this ratio is less than the gasoline stoichiometric ratio. Also; ethanol also has a higher octane number than gasoline. As a higher octane number fuel, ethanol allows it to withstand higher compression ratios when mixed with gasoline [11, 12]. Furthermore, ethanol is a safe source of energy for the purposes of storage and transportation compared to gasoline fuels owing to the higher ignition temperature and flash point [13]. In the literature, it is possible to come across many studies focusing on engine performance effects, such as vibration and noise, exhaust gas emissions of fuel types and mixtures [14]. Taghizadeh et al. (2016) investigated of the effects at different composition rates of ethanol and gasoline blends (2%, 4%, 6%, 8%, 10% and 12%) and at different engine speeds (1600, 1700, 1800, 1900 and 2000 rpm) for the engine performance of the blends. The results clearly demonstrated that the vibration values increased depending on the increasing in the engine. For different fuel compositions, the compositions containing 4% ethanol content for all experiments at the same speed showed the lowest vibration values, while the compositions containing 12% ethanol showed the highest vibration values [15]. In another similar study, Keskin (2010) investigated the vibration and noise values of the fuels with 25% and 50% ethanol content at 1500, 2000 and 2500 rpm engine revolutions. The results of the experiment revealed a linear relationship between vibration values and noise values. When the measurements of the vibration and noise values at the same cycles were evaluated, the experiment values in the pure gasoline blends were lower than the vibration and noise values obtained from the fuels including E25 and E50. The highest vibration and noise values for all mixtures were obtained at 2500 rpm and for E50 fuel type. The results indicated that as the ethanol content increased, there was an increase in vibration and noise. In addition, there are studies in which ethanol is added to diesel, and the results of these studies are similar to those in which ethanol is mixed by gasoline [16]. Ioannis et al. (2011) in their study of different rates (10%, 20% and 30% by vol.) of ethanol and methanol bioenergy sources at different speeds (1000, 1300, 1600 and 1900 rpm) investigated by a spark ignition engine. Compared to the experiment results, at 1000 rpm engine, the lowest vibration value was reached when E10 fuel was used, while E20 fuel with 7.41 m/s^2 at an engine speed of 1900 rpm and E81 fuel with 6.81 m/s^2 had the highest vibration values [17]. Also, there is a great deal of study including harmful exhaust gas emissions arising from fossil fuels in ICEs. Today, the harmful exhaust gas emissions have caused millions of deaths and suffered serious diseases for humans worldwide [18]. Therefore, the reduction of these harmful gases from ICEs has significant importance. In line with these, Palmer (1986) experimentally investigated the impacts of the various composition rates of ethanol and gasoline compositions and his experiment results reported that addition at the rate of 10% ethanol into gasoline increased the engine power output at the rate of 5%. Also, it was observed that each 10% ethanol added into gasoline gave rise an increase to octane number. Palmer highlighted that the addition 10% of ethanol into gasoline might reduce the carbon monoxide emission concentration up to 30% [19]. Alexandrian and Schwalm (1992) showed that the air fuel ratio (AFR) has a great effect on the amount of the CO emission. In the related study, it was highlighted that instead of gasoline alone, the composition of the ethanol and gasoline could cause the less NOx (nitrogen oxides) and CO emissions by making possible the fuel-rich condition [19]. Abdel-Rahman and Osman (1997) explored the effects of adding ethanol at the rate of 10%, 20%, 30% and 40% to gasoline in a variable compression ratio engine. The authors determined that the enhancement of ethanol content increased the octane number whilst decreasing the heating value. The most obvious influence in terms of increasing the octane number was obtained through 10% addition of ethanol into gasoline. Under different engine compression ratios, the optimum composition ratio of ethanol and gasoline was reported as 10% ethanol and 90% gasoline [21]. Bata et al. (1989) experimentally investigated the different ethanol–gasoline blends in engines and observed that the ethanol decreased the CO and UHC (unburned hydrocarbon) emissions to some degree. Owing to the better oxygenated characteristic and the wide flammability of ethanol than pure gasoline, the blends including ethanol caused a reduction in CO emissions [22]. On the other hand, the studies of Rideout et al. (1994) and Chao et al. (2000) reported that the composition of the ethanol and gasoline fuels have increased the emission of acetaldehyde, formaldehyde and acetone between 5.12–13.8 times than those of from gasoline. Even though the using ethanol in engines will cause an increase in the aldehyde emission, this damage to the atmosphere arising from the emitted aldehyde is far less than the poly-nuclear aromatics arising from the burning of the gasoline alone [23, 24]. In comparison with gasoline alone, using a higher rate of alcohol into gasoline can clearly make the air quality better [25].

Based on these literature studies, it is clearly understood that the use of ethanol and gasoline blended fuels in engines can effectively cause the lower the harmful exhaust gas emissions without any modifications in the vehicular systems and fuel tank as well. According to the Turkish Official Gazette no. 30098, come into force on 1 January 2018, the blending of biodiesel with ethanol produced from domestic agricultural products or vegetable waste oils at least 3% and at least 0.5% in the engine has been made compulsory [4]. In the future, it is thought that the amount of ethanol blended into gasoline and diesel will also be increased due to the negative effects of fossil fuels on the environment and human health, the decrease in the reserves of fossil fuels and the increasing oil prices.

II. MATERIAL & METHOD

In this study, we experimentally investigated the effects of the engine performance and harmful exhaust gas emission of ethanol-gasoline blended fuels at different engine speeds and under full load. The ethanol and gasoline were blended by 0% (E0=pure gasoline), 10% (E10) and 20% (E20) volumetrically. The properties of commercial gasoline and ethanol are given in Table 1.

TABLE I
THE PROPERTIES OF COMMERCIAL GASOLINE AND ETHANOL [26, 27].

Property	Gasoline	Ethanol
Chemical formula	C_8H_{15}	C_2H_5OH
Composition (C,H,O) (mass %)	86, 14, 0	52, 13, 35
Oxygen content, mass %	0.0	34.7
Density (kg/m^3)	760	790
Heat of evaporation (kJ/kg)	223.2	725.4
Lower heating value (MJ/kg)	43.5	27.0
Boiling point (°C)	25–215	78.4
Stoichiometric A/F ratio	14.6	9.0
Solubility in water (ml/100 ml H_2O)	<0.1	Fully miscible
Vapor toxicity	Moderate irritant	In small doses
Saturation pressure at 38 °C (kPa)	31	13.8
Auto-ignition temperature (°C)	420	434

A schematic view of the experimental setup is seen in Fig. 1. The experiments for each fuel type were performed at the same operating conditions. In the experiment part of this study, we used the single cylinder, 4-stroke and air-cooled, HONDA GX390 engine and a 15 kW power absorbable electric dynamometer.

In the experimental section of this study, we used the single cylinder, 4-stroke and air-cooled, HONDA GX390 engine and a 15 kW power absorbable electric dynamometer. Technical specifications of the engine are shown in Table 2. Additionally, the vibration data of the system were obtained by a data acquisition device capable of conducting a four-channel VIBROTEST 80 model FFT analysis with a single-axis piezoelectric accelerometer. It has Brüel & Kjaer software and hardware system. After that, the data were analyzed by Hanning filtering method at 6400 resolution. Vibration data up to 5 kHz were obtained in the experiments. The total mean of the vibration data was calculated by the mean square root (RMS) method and the unit of the acceleration is g (m/s^2).

TABLE II
TECHNICAL SPECIFICATION OF HONDA GX390 ENGINE

Brand	Honda
Model	GX 390 H VTE5
Engine type	4-stroke single cylinder OHV petrol engine
Ignition system	Digital CDI with variable ignition timing
Cylinder number	1
Fuel type	Unleaded gasoline
Bore x Stroke	86 x 64 mm
Displacement	389 cm³
Compression ratio	8.2:1
Spesific fuel consumption	230 gr/BG-h
Max. net torque	26.5 Nm / 2.7 kgfm / 2500 rpm
Nominal speed	3600 rpm
Max. engine power	9,6 kW

In addition, all experiments were performed as the engine oil temperature reached 50 ºC. The engine oil temperature was measured by a K type thermocouple. The vibration data only in the vertical direction is taken in this study. The noise of the test engine was measured by the aid of a Svantek 104 model noise measurement device. Technical specification of the noise measurement device is given in Table 3. Before the experiments, this noise device located 1 m from the engine block in accordance with ISO 362-1: 2007 standard.

Table III
TECHNICAL SPECIFICATION OF THE SVANTEK SV 104 NOISE MEASUREMENT DEVICE

Brand	Svantek SV 104
Filtering	A, C and Z
Time constants	Slow, Fast, Impulse
Measurement range	55 dBA RMS÷140.1dBA Pik
Frequency range	30 Hz ÷ 8 kHz
Dynamic range	95 dB
Memory	8 GB

To obtain the torque values of the system, KiTorq System is used in this study and this system has a torque measuring flange system consisting of the Kistler Type 4550A. The technical specification of the torque measurement device is given in Table 4.

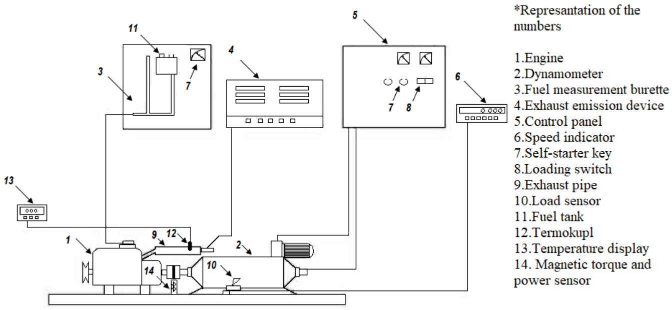


Figure 1. Schematic view of the experimental setup.

TABLE IV
THE TECHNICAL SPECIFICATION OF THE TORQUE MEASUREMENT DEVICE

Rated torque	N.m	500
Max. torque	N.m	2 x rated torque
Accurancy	-	0.05 %
Linearity error including hysteresis	% FSO	0.03
Speed & angle measurement	pulses/rev.	up to 8 192 pulses + Z-pulse
Rated speed	1/min	≤20000
Operating temperature range	°C	10 - 60

In this study, harmful exhaust gas emission values were measured for all experiments and variables. Fort his measurement, the exhaust gas emissions were determined by K Test emission measuring device and the technical specification of this device are given in Table 5.

TABLE V
THE TECHNICAL SPECIFICATION OF THE EXHAUST GAS EMISSIONS MEASUREMENT DEVICE

Brand	K Test
O_2 concentration (%)	0-25 (%)
CO concentration (%)	0-15 (%)
HC (ppm)	0-20.000 (ppm)
CO_2 concentration (%)	0-20 (%)
Lambda	0,5-2,0

III. ERROR ANALYSIS

The experiments cannot be measured with 100% accuracy owing to many factors such as calibration, test conditions-planning, instrument selection, reading, the absence of homogeneity of materials used in experiments, from ambient conditions, the range of measurement devices and even the connection type-points and locations of the measurement probes on the experiment setup [28]. To decrease the effects of these factors, it is suggested that the experiments in the studies were performed at least three times to ensure the reality of the obtained results and to confirm the repeatability under the same conditions, and then reported the averages of this three measurement. Actually, the error and uncertainty analysis are one of the most effective methods to evaluate and determine the experimental results. Hence, the accuracy rates of all measurement devices using the experimental section of this study are given in Table 6. Total error rate (e_r) in this study are calculated using the following equation.

$$e_r = [(0.22)^2 + (0.05)^2 + (0.1)^2 + (0.01)^2 + (0.0001)^2 + (0.1)^2 + (1)^2 + (1)^2 + (0.7)^2 + (1)^2]^{1/2} = \pm 1.89 \% \approx 3.78 \%$$

Confidence level = 96.22 %

TABLE VI
THE ACCURACIES OF THE EXPERIMENTAL DEVICES USING IN THIS STUDY

Measurements	Accuracy in this study
Thermocouples	0.22 %
Torque	0.05 %
O_2 concentration (%)	0.1 %
CO concentration (%)	0.01 %
HC (ppm)	1 ppm
CO_2 concentration (%)	0.1 %
NOx	0.1%
Fuel consumption level	1 %
Speed rate	1 %
Noise level	0.7 %
Vibration level	1 %

IV. RESULTS AND DISCUSSION

In this study, pure gasoline and different volumes of ethanol-gasoline mixtures (10% ethanol + 90% gasoline, 20% ethanol + 80% gasoline) were used for the experiment. Depending on the fuel types and various engine speed, it is aimed to determine the effects of carbon monoxide (CO), hydro carbon (HC), carbon dioxide (CO_2), hydrocarbon (HC) and nitrogen oxide (NOx) emissions and as well as the power, torque, vibration and noise values, specific fuel consumption were investigated. The tests were performed at 2250, 2500, 2750, 3000 and 3250 rpm engine speeds for each fuel type under full load. The findings of the experimental study are mentioned below.

As is known, torque is the ability potential of the engine to work. In ICEs, the internal filling ratio is low and the torque value is less because the filling ratio is low and insufficient at high speeds. Therefore, the most efficient operating conditions are obtained at medium speeds [29]. Power and torque changes depending on the engine speed for all fuel blends are given in Figure 2. As shown in figure x, the engine power and torque values of the ethanol-containing fuels are lower in all cycles compared to gasoline alone. This is due to the fact that ethanol-containing fuels have a lower thermal value than gasoline, as shown in Table 1. Thus, during the combustion of ethanol-containing fuels, less energy is generated at the engine's operating time [30]. According to the experimental results, the maximum motor torque for all fuels reached a maximum value at 2500 rpm.

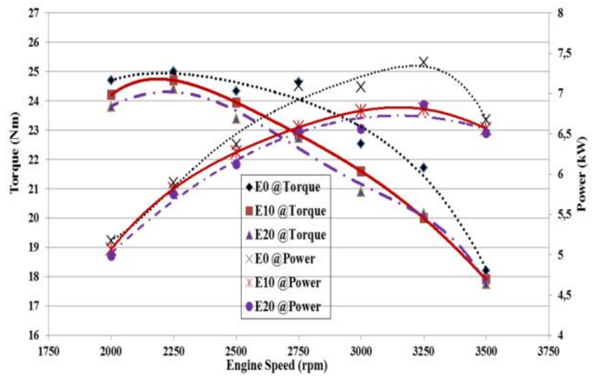


Figure 2. Torque and Power curves for all fuel blends at different engine speed

Specific fuel consumption changes depending on the engine speed and fuel type are given in Fig. 3. Brake specific fuel consumption (BSFC) is a measure of the fuel efficiency of ICEs. Specific fuel consumption increases due to the ethanol content in the fuel mixtures. This is because of the lower heat value of ethanol compared to gasoline alone (Table 1). As the ethanol content in the fuel mixtures increases, the energy amount of the fuel mixtures decreases and the engine consumes more fuel in order to provide the same power under the same operating conditions. As shown in Fig. 3, the minimum specific fuel consumption for all fuel mixtures is around the maximum torque cycle. In ICEs, the speed range in which the highest engine torque is obtained is accepted to be the most efficient operating range. In this range, the high volumetric and combustion efficiency reduces specific fuel consumption and increases engine torque [29]. However, the specific fuel consumption for all fuel blends increases at low and high engine speeds. As the engine generates less power at low speeds, the specific fuel consumption increases for all fuels due to increased frictional forces and reduced volumetric efficiency at high speeds.

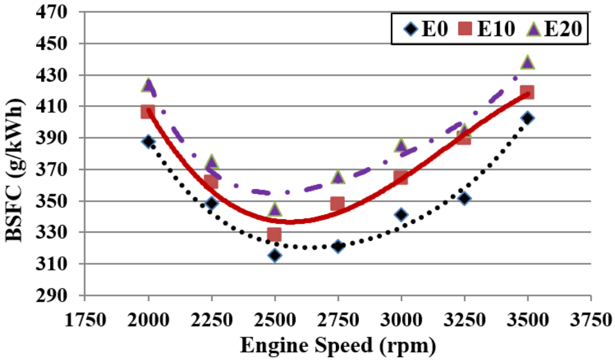
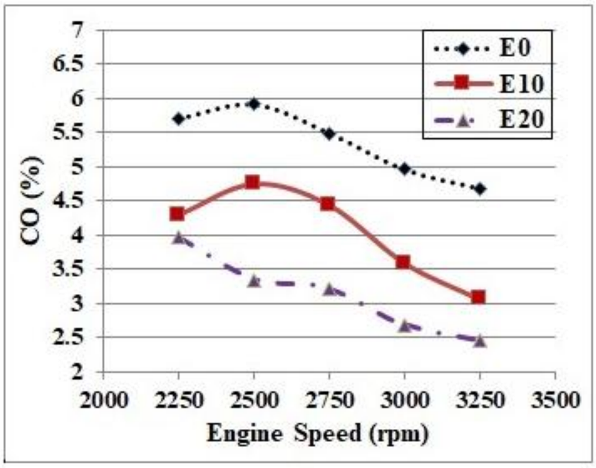
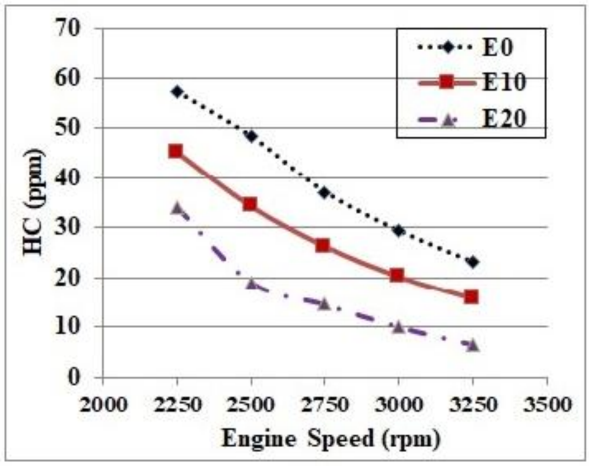


Figure 3. The curves of BSFC and Engine speed

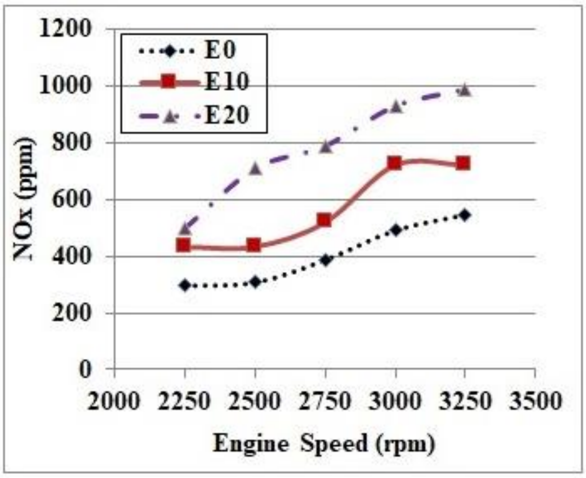
Figure 4 indicates exhaust gas emissions such as CO, HC, CO_2 and NOx depending on engine speed and fuel blends. Figure 4a shows the effects of fuel blends on CO emissions depending on engine speed. As shown in Fig. 4a, CO emissions have been reduced with both increasing the ethanol content in the fuel blends and engine speed. As increasing the ethanol content in the fuel blends brought the air-to-fuel ratio (AFR, λ) as close to 1 as shown in Fig. 5 and consequently increased combustion quality [31. 32]. Additionally, the carbon content of the gasoline is greater than ethanol. Carbon in the fuel turns into carbon monoxide during combustion. Thus, CO emissions also are reduced depending on the ethanol content in the fuel blends. In addition, because the latent heat of evaporation of ethanol is greater than gasoline, the air absorbing into the engine cools at the time of vacuum and the volumetric efficiency increases. The increased volumetric efficiency reduces CO emissions by providing a greater degree of complete combustion. In addition, the high oxygen content of ethanol also leads to a decrease in CO emissions by increasing the combustion quality [33]. At high engine speeds, the air fuel mixture improves combustion as a better homogeneity due to increased turbulence. Therefore, CO emissions tend to decrease at high speeds. Moreover, having a higher combustion rate of ethanol-containing fuels contributed to the full realization of combustion, thus lowering CO emissions [34]. Figure 4b shows the effect of fuel mixtures and engine speed on HC emissions. The main reason for HC emissions is unburned combustion due to the homogeneity of air and fuel mixture. As shown in Fig. 4b, HC emissions are reduced for all fuels depending on engine speed and ethanol ratio. The high oxygen content of ethanol-containing fuels improved the combustion and reduced HC emissions. In addition, the air-fuel ratio of the containing fuels was close to 1 and the HC emissions decreased. With increasing engine speed, the turbulence in the combustion homogenizes the air-fuel mixture and increases the combustion temperature, improves combustion and reduces HC emissions.



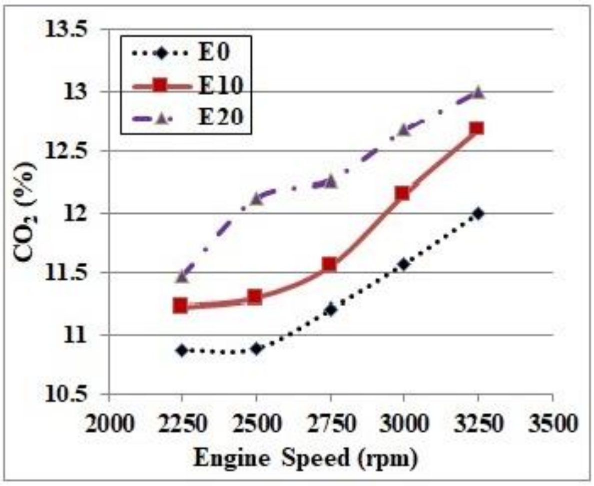
(a)



(b)



(c)



(d)

Figure 4. Exhaust emissions depending on different engine speed a) CO b) HC c) NOx and d) CO_2

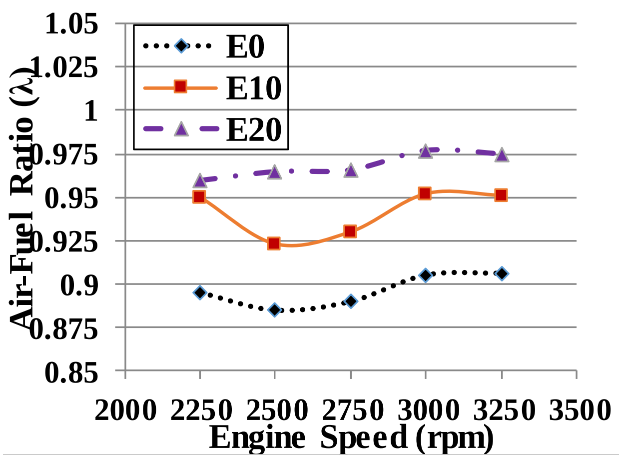


Figure 5. Air-Flow ratio (AFR) depending on the engine speed

Figure 4c shows the effect of fuel mixtures and engine speed on NOx emissions. Oxygen concentration, combustion temperature and time are the main parameters affecting NOx emissions. As shown in Figure 4c, NOx emissions are increased depending on the ethanol ratio and engine speed in the fuel mixtures. The higher the O_2 content of the ethanol-containing mixtures, the higher the burning temperature together with NOx formation. Furthermore, in the combustion process of ethanol-containing fuels, the air-fuel ratio is closer to the stoichiometric value, increasing the flame temperature and increasing NOx emissions. Also, Figure 4c shows the effect of fuel mixtures and engine speed on NOx emissions. Oxygen concentration, combustion temperature and time are the main parameters affecting NOx emissions. As shown in Fig. 4c, NOx emissions are increased depending on the ethanol ratio and engine speed in the fuel mixtures. The higher the O_2 content of the ethanol-containing mixtures, the higher the burning temperature together with NOx formation.

Furthermore, in the combustion process of ethanol-containing fuels, the air-fuel ratio is closer to the stoichiometric value, increasing the flame temperature and increasing NOx emissions. Additionally, Figure 4d shows the effects of fuel blends on CO_2 emissions depending on the engine speed. As the amount of ethanol in the mixture increased, CO_2 emissions also increased. Theoretically, only water (H_2O) and carbon dioxide (CO_2) should be produced in the ideal conditions by combustion of hydrocarbon fuel [35]. The main reason for this case is the use of more oxygen-containing fuel to obtain the same output power [36]. More CO_2 emissions have been produced due to combustion with ethanol-containing fuels [37]. The increase at engine speed and the increase in CO_2 emissions indicate that combustion is high for all fuels at high speeds. Obtaining more CO_2 emissions with ethanol-containing fuels is due to the fact that O_2 in ethanol-containing fuels reacts with unburned carbon atoms during combustion to increase CO_2 formation. A greater amount of CO_2 in exhaust emissions indicates the complete burning of the fuel [36]. Additionally, the vibration values and engine noise level were calculated according to the data obtained for all fuels depending on engine speed are given in Fig. 6. As a result of the experiments, the smallest acceleration values obtained by E0 fuel were obtained by E20 fuel. Due to the high oxygen content of ethanol-containing fuel blends, the reaction rate of combustion increases and higher flame speeds are reached. This increases the in-cylinder pressure increase rate (dp/dt). Moreover, the higher latent heat of evaporation of ethanol increases the volumetric efficiency of the engine by cooling the air entering the engine. This can increase the pressure increase rate and maximum pressure in the cylinder dp/dt. Ethanol-containing fuels increase the in-cylinder pressure increase and pressure for the cylinder increased engine vibration and noise levels.

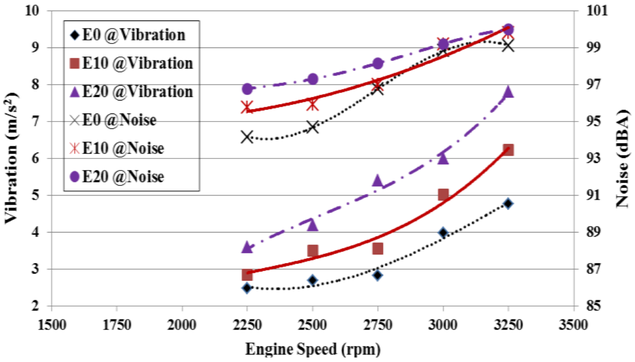


Figure 6. Vibration and Noise levels depending on the engine speed

To sum up, carbon monoxide and hydrocarbon emissions arising from burning ethanol and gasoline blends were reduced as compared to gasoline alone. On the other hand, the increase in ethanol content in the fuel blends caused the increase in carbon dioxide and nitrogen oxide emissions. In addition, the ethanol content caused in a certain increase in specific fuel consumption, vibration and noise levels. However, ethanol has the potential to be used on the vehicle without any modifications. It is suitable for use in vehicles by improving the negative properties resulting from the use of ethanol. As an advice for future works, experiment numbers could be decreased by a mathematical optimization study. There are a number of various studies applying different optimization method and presented good results in the literature [38-43] because the optimization helps not only to achieve the optimum value with less trial but also to make the possible evaluated the parameters and used effectively.

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