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Experimental Investigation of the Effects of E85 and Gasoline on NO Emission in a Spark Ignition Engine

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Anahtar Kelimeler

Buji ile Ateşlemeli Motor
Alternatif Yakıt
E85
Motor Performansı
NO Emisyonu

Graphical/Tabular Abstract (Grafik Özet)

In this study, the effects of E85 and gasoline on NO and BSNO emissions have been investigated experimentally by considering ignition timing and relative air/fuel ratio in a spark ignition engine. / Bu çalışmada, bir buji ile ateşlemeli motorda ateşleme zamanı ve hava fazlalık katsayısı dikkate alınarak E85 ve benzinin NO ve özgül NO emisyonları üzerindeki etkileri deneysel olarak araştırılmıştır.

***Figure A**: Experimental setup and BSNO / **Şekil A:** Deneysel düzenek ve özgül NO*

Highlights (Önemli noktalar)

- *According to all experimental data, the gravimetric fuel consumption and BSFC for E85 compared to gasoline increased on average by 39.3% and 37.5%, respectively. / Tüm deneysel verilere göre, benzine kıyasla E85 için kütlesel yakıt tüketimi ve FÖYT sırasıyla ortalama %39,3 ve %37,5 arttı.*
- *An average of 37.5% reduction at the values of the 1.05 and 1.1 RAFR where the NO emission peaks, in general, were obtained in E85 fuel compared to gasoline. / E85 yakıtında genel olarak NO emisyonunun pik yaptığı 1,05 ve 1,1 HFK değerlerinde benzine göre ortalama %37,5 azalma elde edilmiştir.*
- *Considering the maximum NO point of 1.05 or 1.1 RAFRs, a 38.4% reduction in BSNO was obtained with E85 compared to gasoline. / Maksimum NO noktası olan 1,05 veya 1,1 HFK değerleri dikkate alındığında, E85 ile benzine kıyasla özgül NO'da %38,4 oranında azalma elde edilmiştir.*

Aim (Amaç): *The aim of this study is to experimentally investigate the effect of gasoline and E85 on NO emissions in an SI engine at the same operating conditions. / Bu çalışmanın amacı aynı çalışma koşullarında buji ile ateşlemeli bir motorda benzin ve E85'in NO emisyonları üzerindeki etkisini deneysel olarak incelemektir.*

Originality (Özgünlük): *In this study, the effects of E85 and gasoline on NO emissions at the same operating conditions were investigated experimentally by considering ignition timing and relative air/fuel ratio in a spark ignition engine. / Bu çalışmada, bir buji ile ateşlemeli motorda ateşleme zamanı ve hava fazlalık katsayısı dikkate alınarak aynı çalışma koşullarında E85 ve benzinin NO emisyonları üzerindeki etkileri deneysel olarak araştırılmıştır.*

Results (Bulgular): *The experimental results showed an overall reduction in NO and BSNO emissions for E85 compared to E0; moreover, in the poor air/fuel mixtures, especially at the values of 1.05 and 1.1 RAFR where the NO emission peaks, the reduction was more significant and considerable. / Deney sonuçları, E0'a kıyasla E85 için NO ve özgül NO emisyonlarında genel bir azalma olduğunu gösterdi; ayrıca, fakir hava/yakıt karışımlarında, özellikle NO emisyonunun zirve yaptığı 1,05 ve 1,1 HFK değerlerinde azalmanın daha belirgin ve dikkate değer olduğu görülmüştür.*

Conclusion (Sonuç): *Compared to gasoline, despite the increase in gravimetric or volumetric fuel consumption in the usage of E85, the remarkable decrease in NO and specific NO emissions stands out as the main result obtained in the research. / Benzin ile karşılaştırıldığında E85 kullanımında kütlesel veya hacimsel yakıt tüketimi artmasına rağmen NO ve özgül NO emisyonlarındaki dikkate değer azalma araştırmada elde edilen temel sonuç olarak göze çarpmaktadır.*

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Abstract

Energy need is one of the indispensable needs of human beings. At this point, the important thing is to use the available resource that is sustainable, economical, and sensitive to the ecosystem. For this reason, alternative fuels will maintain their importance in the future as they do today. Internal combustion engines continue to be used as power plants for conventional and hybrid vehicles. The sustainability of internal combustion engines depends on their energy consumption and the emissions released. In this study, the effects of E85 and gasoline on NO emissions have been investigated experimentally by considering ignition timing and relative air/fuel ratio in a spark ignition engine. The experiments have been performed on the Ricardo Hydra research engine at 2000 rpm engine speed and a 10:1 compression ratio. The experimental results show that engine output power obtained using E85 was similar to or higher than that of E0. The exhaust gas temperatures for E85 decreased by an average of 22.6 °C, compared to E0. When all experimental data obtained with E0 and E85 were compared with each other, it was seen that gravimetric fuel consumption and brake specific fuel consumption were increased on average by 39.3% and 37.5%, respectively. The results of this study show that the improvement of E85 in NO emission is remarkable. Considering the maximum NO point at 1.05 or 1.1 relative air/fuel ratio, a 38.4% reduction in brake specific NO was obtained with E85.

Buji ile Ateşlemeli Bir Motorda E85 ve Benzinin NO Emisyonuna Etkilerinin Deneysel İncelenmesi

Makale Bilgisi

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Öz

Enerji ihtiyacı insanoğlunun vazgeçilmez ihtiyaçlarından biridir. Bu noktada önemli olan elde edilebilir kaynağı sürdürülebilir, ekonomik ve ekosisteme duyarlı kullanmaktır. Bu nedenle alternatif yakıtlar bugün olduğu gibi gelecekte de önemini koruyacaktır. İçten yanmalı motorlar konvansiyonel ve hibrit araçlar için güç kaynağı olarak kullanılmaya devam etmektedir. İçten yanmalı motorların sürdürülebilirliği, enerji tüketimine ve emisyon salınımlarına bağlıdır. Bu çalışmada, bir buji ile ateşlemeli motorda ateşleme zamanı ve hava fazlalık katsayısı dikkate alınarak E85 ve benzinin NO emisyonları üzerindeki etkileri deneysel olarak araştırılmıştır. Deneyler, 2000 rpm motor devrinde ve 10:1 sıkıştırma oranında Ricardo Hydra araştırma motorunda gerçekleştirilmiştir. Deneysel sonuçlar, E85 kullanılarak elde edilen motor çıkış gücünün E0'ınkine benzer veya daha fazla olduğunu göstermektedir. E85 için egzoz gazı sıcaklıkları, E0'a kıyasla ortalama 22,6 °C azaldı. E0 ve E85 ile elde edilen tüm deneysel veriler birbiriyle karşılaştırıldığında, kütlesel yakıt tüketiminin ve fren özgül yakıt tüketiminin sırasıyla ortalama %39,3 ve %37,5 arttığı görüldü. Bu çalışmanın sonuçları, özellikle E85'in NO emisyonundaki iyileştirmesinin dikkat çekici olduğunu göstermektedir. 1,05 veya 1,1 hava fazlalık katsayısında maksimum NO noktası dikkate alındığında, E85 ile fren özgül NO emisyonunda %38,4'lük bir azalma elde edildi.

1. INTRODUCTION (GİRİŞ)

Internal combustion engines continue to meet the energy needs of vehicles as stand-alone power plants or in hybrid systems. Diesel and petrol engines have been used for more than 100 years. During this period, numerous research and development studies have been conducted and continue to be conducted for improving vehicles and these engines. Studies on using alternative fuels in these engines and improving pollutant emissions are among the essential issues that researchers focus

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on. Furthermore, as it is today, the most severe problem with internal combustion engines in the future will be the pollutant exhaust emissions caused by combustion.

In this study, ethanol was discussed both as an alternative fuel to gasoline and in terms of its effect on NO emission. There are several studies on ethanol as an alternative fuel in the literature. In various studies in the literature, it can be seen that ethanol and ethanol blends have some prominent features, such as octane rating, heating value, latent heat of vaporization, and stoichiometric air/fuel ratio in terms of their effect on engine performance and exhaust emissions. Some of these properties of gasoline and ethanol, especially relevant to SI engines, are given in Table 1.

Table 1. Some properties of gasoline and ethanol (Benzin ve etanolün bazı özellikleri) [1-5]

Properties	Gasoline	Ethanol
Formula	C_4 to C_{12}	C_2H_5OH
Density, kg/L@20 °C	0.7-0.75	0.789
Lower heating value, MJ/L	30-33	21.1
Latent heat of vaporization, kJ/kg	349	923
Stoichiometric air/fuel ratio	14.7	9
RON	88-98	111
Laminar flame speed, cm/s	33	39
Adiabatic flame temperature, °C	1970	1923
Autoignition temperature, °C	257	423

Generally, compared to gasoline, the higher knock resistance, latent heat of vaporization, and laminar flame speed of ethanol are considered to be advantageous for improving the engine torque and power in SI engines. However, particularly the lower heating value and stoichiometric air/fuel ratio can be considered a disadvantage of ethanol in fuel consumption. These specifications can cause an increase in the volumetric or mass fuel consumption, which depends on engine operating conditions and the amount of ethanol in the blends. These effects can be observed in some studies [6-10] in the literature.

The oxygen content and low stoichiometric air/fuel ratio can also stand out as advantages in improving exhaust emissions. As well as the effects of these specifications depend on engine operating conditions, especially CO and HC emissions can be decreased. Both emissions peak in the rich mixtures and decrease in lean mixtures. This feature so-called leaning effect allows the engine to run at a leaner mixture than gasoline and provides extra oxygen for combustion. In the literature [11-18], the positive impact of the leaning effect of oxygenated fuels on CO and HC emissions has been mentioned. When it comes to NO_x emissions, it can be stated that NO_x emissions are influenced by temperatures in the combustion chamber besides the air/fuel ratio. At this point, it can be expressed that lower adiabatic flame temperature may be an advantage.

It can be seen that researchers from all over the world have studied the effects of alternative fuels on engine performance and exhaust emissions in the ICEs in literature.

Singh et al. [19] investigated the effects of ethanol/gasoline blends on engine performance and emissions. They used E0, E5, E10, and E20 ethanol/gasoline blends in their study. They achieved up to a 2.5% increase in engine performance and up to a 2.5% decrease in BSECs with ethanol blends. Also, the E20 decreased CO emission and HC emission by 65% and 38%, respectively, but doubled NO_x emissions. Hasan et al. [20] investigated the effect of the combustion chamber geometry and ethanol/gasoline blends on combustion characteristics and exhaust emissions. In this study, the blends contained 10% ethanol and 20% ethanol, using five different compression ratios from 4:1 to 10:1. They expressed that changing the compression ratio influenced NO_x emissions more than other emissions. Also, ethanol blends decreased NO_x emissions owing to a higher heat vaporization rate and a lower adiabatic flame temperature compared to gasoline. Turner et al. [2] stated that as the ethanol ratio in the ethanol/gasoline blend increased, combustion efficiency, engine efficiency, and in-cylinder pressure were higher, CO emissions and NO_x emissions decreased or were similar to gasoline. In their study, it was indicated that these improvements were obtained because of better evaporation, higher laminar flame velocity, and improved combustion. The study by Farrell et al. [21] reported that the burning velocity of ethanol was higher than iso-octane, which is a highly branched alkane. A similar result was obtained by Tian et al. [22]. They found that ethanol had the highest laminar flame speed in their study. Also, it was emphasized that the laminar flame speed of ethanol was approximately 30-40% higher than the 2,5-dimethyfuran (DMF). Furthermore, gasoline was slightly faster than DMF.

The knocking resistance of the ethanol at relatively high compression ratios comes outs concerning engine performance. The engine brake torques of gasoline (E0) and ethanol-gasoline blend (E60) were compared in the Ricardo Hydra research engine and Cussons-P8800 type standard engine testbed in an experimental study by Topgül and Yücesu [23]. Also, they researched knocking using Kistler 6121 type piezoelectric pressure transducer and Cussons P4410 engine electronic indicating system. At the operating conditions of 2000 rpm engine speed, 10:1 CR, and λ=1, normal combustion was observed at 22 °CA ignition timing, but they reported that slight knocking occurred at 24 °CA. When the ignition timing was increased to 36 °CA, they observed intensive knocking on the oscilloscope's screen. Moreover, the researchers found that there was not any knocking at the same engine operating conditions depending on ignition timing for E60. A similar result was found in the study by Kalghatgi et al. [24], which stated having a higher resistance of ethanol to auto-ignition provided a reduction in the possibility of super knock. Sasaki and Nakata [25] obtained that ethanol has the highest pre-ignition temperature at low engine speed.

This paper deals with the NO emission of a spark ignition engine fueled by gasoline and E85. The parameters, which are extremely effective on NO emission, such as the relative air/fuel ratio (RAFR) and the ignition timing (IT) were considered in this experimental study. Ricardo Hydra research engine was used in the experiments since the abovementioned parameters could be adjustable smoothly in this engine. This study aimed to observe the variation in NO emissions associated with these parameters and fuels. In the experiments, it was purposed to obtain the variation of the NO emission under operating conditions based on the stoichiometric air/fuel ratio rather than the leaning effect of the ethanol. In fact, in this comparison, it can be expressed that the amount of heat supplied into the cylinder chamber was considered equal. In addition to NO emission, engine brake power, brake specific fuel consumption (BSFC), brake specific energy consumption (BSEC), and brake thermal efficiency (BTE) were also examined.

2.MATERIALS AND METHODS (MATERYAL VE METOD)

The experimental study was conducted on a single-cylinder, four-stroke, water-cooled, and variable compression ratio Ricardo Hydra research engine. The other specifications of the test engine seen in Fig. 1 are given in Table 2.

The other equipment in the experiments can also be seen in Fig. 1. The experiments were performed at a Cussons P8800 type standard engine testbed consisting of a test engine, an electrical dynamometer, which is a DC machine, a control console, and auxiliary equipment such as engine inlet, cooling, and lubricating oil systems. Engine speed, throttle, ignition timing, fuel injection duration, and other test system controls were made with the help of the control console. Moreover, this console was used for monitoring the engine speed, brake torque, ignition timing, oil pressure, coolant level, system faults, and temperatures such as inlet air temperature, exhaust temperature, oil temperature, and inlet/outlet coolant temperatures.

Table 2. The specifications of the Ricardo Hydra research engine (Ricardo Hydra araştırma motorunun özellikleri)

Type	Overhead camshaft, port fuel injection, and SI engine	
Cylinder dimensions (Bore X Stroke)	80.26 X 88.9 mm	
Compression ratio (Adjustable)	5:1 - 13:1	
Ignition timing (Adjustable)	70º BTDC - 20º ATDC	
Valve timing	Intake	Exhaust
Opens Closes	12° BTDC 56° ABDC	56° BBDC 12° ATDC

The gravimetric fuel consumption was carried out by using scales Ohaus GT 8000 with an accuracy of 0.1 g and a stopwatch Robic SC-700. A Meriam Z50MC2-4F model laminar flow element with a 0.72% reading accuracy was used to measure the airflow rate and air density. A Sun Gas Analyzer MGA 1500s device was used to measure the concentrations of exhaust emissions. The emission values were collected with the help of the RS-232 connection from the exhaust emission device to the computer.

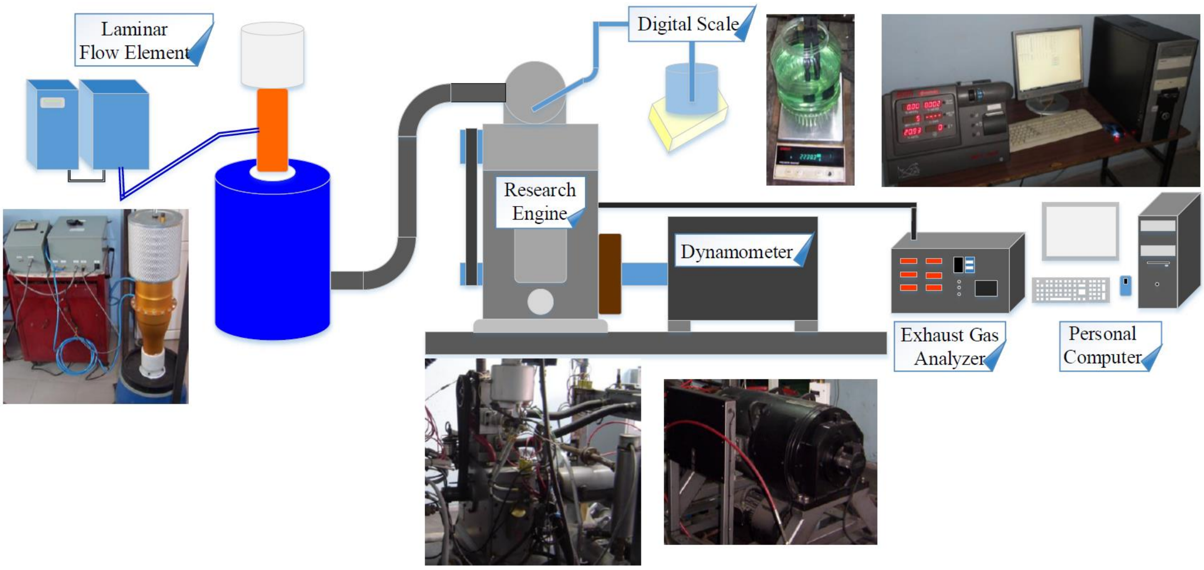

Figure 1. The experimental setup (Deneysel düzenek)

Unleaded gasoline and E85 were used in the experiments as test fuels. The specifications of the unleaded gasoline are given in Table 3 and it is called E0 in this paper. The other test fuel, E85, was prepared as consisting of 85% absolute ethanol (99.5%) and 15% unleaded gasoline by volume. The specifications of each fuel in the blend are seen in Table 3 and 4.

Table 3. The technical specifications of the unleaded gasoline (Kurşunsuz benzinin teknik özellikleri)

Property Item	Method	E0
Density (kg/m^3 at 15 °C)	TS 6311	772.9
RVP (kPa)	ASTM D 323	51.9
Distillation (vol. %) 70 °C 100 °C 150 °C	TS 1232 EN ISO 3405	 18.7 41.4 87.6
RON	FTIR	96.1
MON		85.8

Table 4. The specifications of the ethanol (Etanolün özellikleri)

Property Item	Ethanol
Molecular weight (g)	46.07
Density (g/cm^3)	0,798
Boiling point (°C)	78.5
Flash point (°C)	9-11

The experiments were conducted at a constant load (WOT), 2000 rpm engine speed, and 10:1 compression ratio. The research engine was equipped with variable CR, but CR was adjusted to 10:1 to obtain as much data as possible without knocking specifically for E0. The experiments were performed at different values of the relative air/fuel ratio (0.85-1.2) and the ignition timing (10-26 °CA BTDC). All the tests were performed at the engine working water temperature and oil temperature.

The data from the experimental study contain errors and uncertainties mainly resulting from operators and devices, such as instrument selection, calibration, test procedure, environment, condition, observation, and reading [26, 27].

To verify the accuracy of the experiments, Eq. (1) was used similar to the literature [28-31].

$$w_R = \left(\sum_{i=1}^{n} \left(\frac{\partial R}{\partial x_i} w_i \right)^2 \right)^{0.5} \tag{1}$$

where w_R is the total uncertainty in the computed value, R is a function of the independent variables x_1, x_2,…, x_n and w_1, w_2, …, w_n are defined uncertainties related to the independent variables [32, 33]. The uncertainty of the computed results and accuracy of the measurements and are given in Table 5.

Error bars can be used to represent variations in data and experimental uncertainty in an experimental study. For this purpose, error bars were used in studies in the literature. For example, the error bars in the study by Rocha et al. [34] are based on the accuracy of the measuring devices used for data collection.

In each experiment, the data from the control console were recorded three times and the emission data were acquired five times during the measurement. The averages of each data group are used in the figures of this study. All the figures in this study include error bars based on uncertainty to show the maximum deviation in the data. If error bars are not seen at some points in the figures, this is due to their small values or the vertical scale range of the graph. Also, the difference values obtained from comparing E0 and E85 have been more than the deviation of the measured or computed data in general. This situation can be seen in the figures.

Table 5. Accuracies of the measurements and uncertainty of computed results (Ölçümlerin doğruluğu ve hesaplanan sonuçların belirsizliği)

Measurements	Accuracy
Speed (rpm)	±2
Torque (Nm)	±0.1
Time (s)	±0.5%
Fuel (g)	±0.1
Temperatures (°C)	±1
Heating value (kJ/kg)	±1%
Air flow (g/h)	±0.72%
NO (ppm)	±5%
Computed results	**Uncertainty (%)**
Engine power	0.75
Fuel flow rate	0.83
BSFC	1.12
Total heat input	1.3
BTE	1.5
BSEC	1.5
RAFR*	1.1
BSNO	5.1

* RAFR (λ) is defined as the actual air/fuel ratio to the stoichiometric air/fuel ratio.

3. RESULTS AND DISCUSSIONS (BULGULAR VE TARTIŞMA)

The variations of the NO emission versus RAFR and IT are given in Fig. 2. As seen in the figure, NO emission reaches a peak value at a leaner air/fuel ratio from the stoichiometric mixture and it also increases depending on the increase in ignition timing. It can also be seen that the variation trends are the same for both test fuels.

The term nitrogen oxides (NO_x) is more commonly known as nitrogen oxide (NO) and nitrogen dioxide (NO_2); however, primarily NO stands out in SI engines [35, 36]. Approximately 90-98% of all NO_x emissions during engine operation are due to NO emissions [37, 38]. The formation of nitrogen oxide primarily depends on peak temperature and oxygen concentration. NO reaches the highest value at an air/fuel ratio slightly lean from the stoichiometric air/fuel ratio because of the sufficient oxygen and higher combustion temperature [36-39].

Most of the NO emission formation, except for lean air/fuel ratios at low temperatures, can be explained by the extended Zeldovich mechanism. The first and second reactions (Eq. 2 and 3) gain importance in the lean and slightly rich air/fuel mixtures over the temperature of 1500 °C. Eq. (4) becomes prominent regarding rich mixtures [35, 40, 41].

$$O + N_2 = NO + N \tag{2}$$

$$N + O_2 = NO + O \tag{3}$$

$$N + OH = NO + H \tag{4}$$

Heywood [35] has expressed the initial NO formation rate as seen in Eq. (5) in addition to these NO formation mechanisms.

$$\frac{d[NO]}{dt} = \frac{6 \cdot 10^{16}}{T^{0.5}} \cdot \exp\left(\frac{-69090}{T}\right) \cdot [O_2]_e^{0.5} \cdot [N_2]_e \tag{5}$$

The exponential term in the last equation depends strongly on the temperature. As a result, high temperatures and amounts of oxygen lead to high NO formation rates [35]. Briefly, all engine-related parameters that support these reactions can influence the formation of the nitrogen oxides, such as air/fuel ratio, ignition timing, compression ratio, engine load, inlet air temperature, and fuel type [37, 38, 40].

When an overall assessment is made, it can be stated that the variation in the NO emission in Fig. 2 is a usual situation. When the air/fuel ratio effect on the formation of the nitrogen oxides is considered, it can be expressed that nitrogen oxides reach a peak value at λ=1.05-1.1 [36, 38]. Concerning ignition timing, it can be stated that retarding ignition timing increases the exhaust gas temperature, which decreases the peak combustion temperature. Because of this, nitrogen oxides reduce [38, 42].

According to the effect of the fuel type, an overall reduction in NO emissions for E85 compared to E0 can be noticed when Fig. 2 is analyzed. This reduction in NO emission is more apparent and considerable in the poor air/fuel mixtures. An average of 37.5% reduction at the values of the 1.05 and 1.1 RAFR where the NO emission peaks, in general, were obtained in E85 fuel compared to that of gasoline. At a stoichiometric air/fuel ratio, this value was approximately 25%. In the rich region (λ=0.85, 0.9, and 0.95), an average 20% reduction in NO emission was obtained using E85.

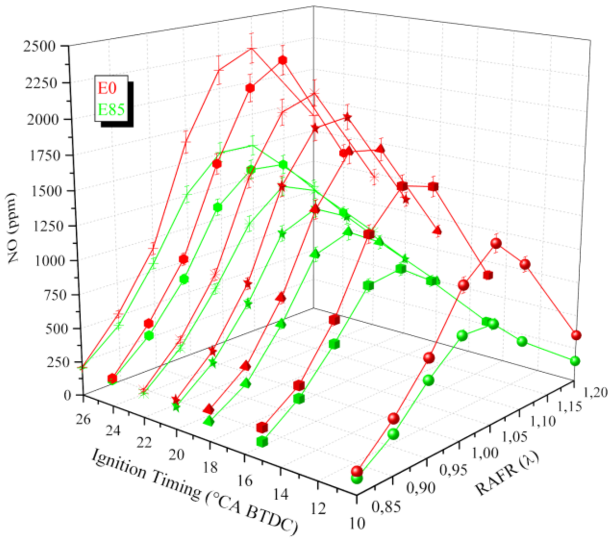

Figure 2. The variation of the NO emission depending on RAFR and ignition timing (Ateşleme zamanı ve HFK'ye bağlı olarak NO emisyonunun değişimi)

The advantages of having lower adiabatic flame temperature and higher heat of vaporization of the possession of ethanol are outstanding specifications in the literature. These specifications support a reduction in NO_x emissions. The study by Nakata et al. [43] showed that an increase in thermal efficiency and a decrease in NO_x were obtained owing to higher combustion speed, lower cooling heat loss, and smaller combustion gas temperature than gasoline. Kumar et al. [44] found that E85 provided about a 30% decrement in NO_x emission compared to E10 during the driving cycle. Park et al. [45] stated that ethanol can reduce engine-out NO_x emissions. Tang et al. [46] studied the effects of ABE (acetone-butanol-ethanol) ratios on engine performance and emissions. Researchers found that increasing the ratio of ABE provided a dramatic reduction in the formation of NO emission because of the lower peak combustion temperature with the charge cooling effect.

In literature, some studies deal with the improvement effect of NO_x emissions with the use of ethanol blends in diesel engines, too. Rakopoulos et al. [47] emphasized that ethanol blends had slightly lower NO_x emissions than neat diesel fuel and higher percentages of ethanol blends promoted further reduction in NO. The study by Morsy [48] stated that ethanol/water mixtures except pure ethanol fumigation decreased NO emission compared to the neat diesel fuel. Şahin et al. [49] pointed out that lower NO_x emissions could be obtained using ethanol fumigation, and they found that NO_x emissions decreased by approximately 8.5%, 9.79%, and 11.02% for three different fuel delivery rates (1/1, 3/4, and 1/2), respectively.

On the contrary, some studies have reported that NO_x emissions increase. Hasan et al. [50] expressed that methanol and biodiesel mixed with diesel increased the levels of NO_x due to the availability of oxygen in the molecular structure of these fuels. Zhao et al. [51] found that diesel fuel has lower NO_x levels than diesel/alcohol blends. They stated that compared to alcohol blends, diesel had a shorter ignition delay due to the lower heat of vaporization and higher cetane number. Also, it is emphasized in this study that the presence of oxygen in alcohol blends promotes combustion and provides a higher burning speed.

Similar results have been reported in some studies dealing with spark ignition engines. Masum et al. [52] investigated the effects of alcohol blends on the performance and exhaust emissions in a multi-cylinder SI engine. They found that M20, E20, P20, and B20 blends increased NO_x emissions compared to pure gasoline by 20%, 32%, 14.5%, and 11%, respectively. They showed the reason as a possible effect of the high amount of oxygen in the alcohol blends. Zhao et al. [53] found that methanol/gasoline blends caused an increase of 175%-233% in NO_x emissions. They stated that higher flame propagation speed and combustion temperature may have a greater effect on this result.

Hsieh et al. [12] noted that engine operating conditions had a greater effect on NO emissions rather than ethanol content in their study. Briefly, engine operating conditions such as air/fuel ratio, ignition timing, compression ratio, engine speed, inlet air temperature, and EGR rate influence NO_x emissions [16].

Fig. 3 shows the variation of the exhaust gas temperature in both test fuels depending on RAFR and IT. It can be seen in this figure that the exhaust gas temperature decreases for E85 compared to E0. The difference in the exhaust gas temperature of E0 and E85 was approximately an average of 22.6 °C.

It was mentioned in the study by Turner et al. [2] that a decrease in exhaust temperature may result from a reduction in the flame temperature. Moreover, it was expressed that the ethanol content is increased from 0% to 100% in the ethanol/gasoline blend, higher flame speed, better evaporation, and similar or reduced NO_x emissions were obtained, and the engine efficiency increased compared to baseline gasoline. Renzi et al. [54] reported that exhaust gas temperatures with E50 and E80 are lower than those with gasoline. They even achieved a 100 K reduction in exhaust temperature with the E80 compared to the E00 at 3000 rpm. The researchers suggested that this result is due to the leaner mixture and the higher cooling effect with the evaporation of the alcohol. Masum et al. [55] expressed that E15 caused a 2.2% lower exhaust gas temperature than gasoline because of the lower heating value of ethanol. A similar result was obtained by Agarwal et al. [56].

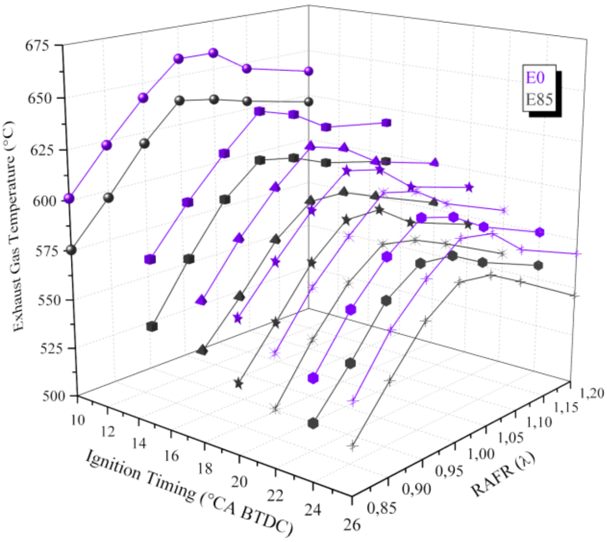

Figure 3. The variation of the exhaust gas temperature depending on RAFR and ignition timing (Ateşleme zamanı ve HFK'ye bağlı olarak egzoz gaz sıcaklığının değişimi)

The variations in various consumption terms and efficiency of both fuels versus IT and RAFR can be seen in Fig. 4 to 7. In these figures, specific values of the RAFR and ignition timing have been chosen as an example to show the change of terms more clearly.

The variation of the brake power, BSFC, and BTE of both fuels versus ignition timing at λ=1 can be seen in Fig. 4. The ignition timing was changed between 10° and 26° BTDC in the experiments. As seen in Fig. 4, engine power rises when the ignition timing is increased from 10° BTDC to MBT depending on the fuel type and then decreases toward 26° BTDC. Because of the variation in the engine power, higher brake thermal efficiency was obtained using E85, but BSFC increased due to the lower heating value of E85.

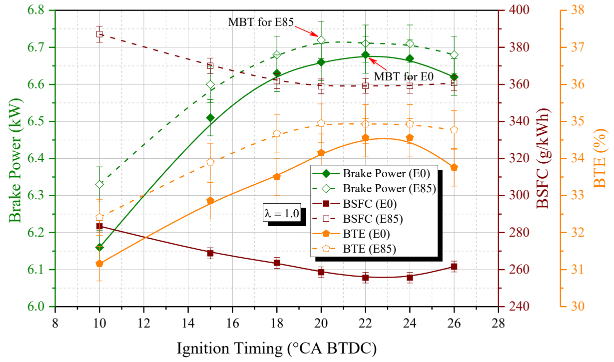

Figure 4. The variation of brake power, BSFC, and BTE of both fuels versus ignition timing (Ateşleme zamanına göre her iki yakıtın motor gücü, FÖYT ve FTV'nin değişimi)

The variation of the brake power and BSFC of both fuels versus RAFR at MBT of each test fuel can be seen in Fig. 5. In the experiments, the RAFR was changed between 0.85 and 1.2. As seen in Fig. 5, the maximum engine power is obtained at 0.9 or 0.95 RAFR due to the higher flame speed. Also, the minimum BSFC was obtained at 1.05 or 1.1 RAFR due to higher brake thermal efficiency.

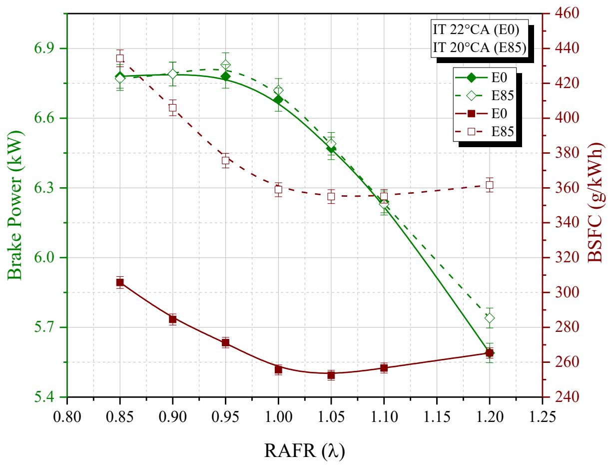

Figure 5. The variation of the brake power and BSFC versus RAFR (HFK'ye göre motor gücü ve FÖYT'nin değişimi)

It can be seen that E85 has higher fuel consumption than E0 as illustrated in Fig. 5. The gravimetric air/fuel ratio of E85 is 9.9 and that of gasoline is 14.7 [1]. If the engine consumes an equal quantity of air in both fuels under the same operating conditions, it means that there is a need for more E85 fuel compared to gasoline. Moreover, the lower heating value of E85 is effective for the fuel quantity of fuel injection per cycle. As stated in the literature [1], the lower heating value of E85 (average 22.65 MJ/L) is approximately 39% less than that of gasoline (average 31.5 MJ/L). Thus, there is a need for higher fuel flow rates for E85 fuel in the fuel delivery system. Erkoca [57] stated that the engine needed more E85 compared to gasoline, so BSFC increased by 36-45%. In their study, Turner et al. [58] used injectors that provide more fuel flow of 425 cc/min for E85 versus 300 cc/min for gasoline at a pressure of 3 bar. Wicker et al. [59] suggested that the E85 injectors should provide approximately 40% more fuel compared with gasoline stock injectors for the effective controlling of the air/fuel ratio of ECM. Davis and Heil [60] used the new injectors having 50% more static flow rate instead of the OEM in their study, which dealt with modifying a Chevrolet Silverado to convert to operation with E85. Boyle et al. [61] converted a 1999 Chevrolet Silverado to run with E85 fuel. They emphasized that in theory, 39.1% more fuel flow for E85 is necessary compared to gasoline. However, they used injectors with a 2.01 mL/s fuel flow rate instead of 1.65 mL/s using a more efficient burning of ethanol and the modifications of the engine like a higher compression ratio, supercharging, etc. These injectors had 30.7% more flow compared with stock units.

The amount of fuel consumed by weight was obtained similarly to the literature in this study. The fuel mass fuel rate of E85 was on average 39.3% more than compared to that of gasoline. This is because of the lower heating value and air/fuel ratio of ethanol. Also, this situation affected BSFC. BSFC for E85 was obtained on average by 37.5% more compared to that of gasoline.

The energy input into the combustion chamber per second, in other words total heat input, it can be seen in Fig. 6 that the values of the total heat input for E0 and E85 are quite close to each other although the fuel mass flow rate of E85 is more than that of E0. When both fuels were compared with each other, the maximum difference in total heat input obtained was 1.35%.

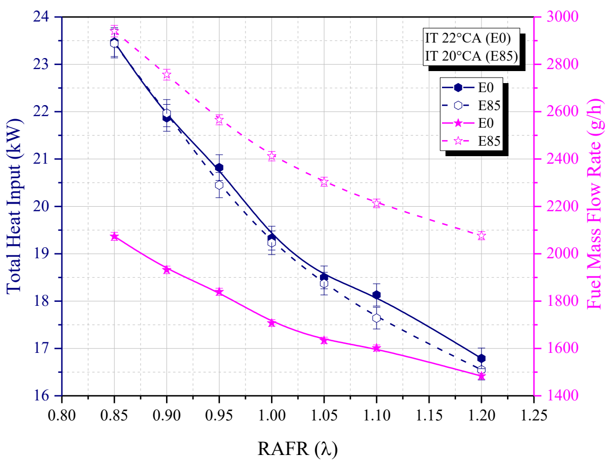

Figure 6. The variation of the total heat input and fuel mass flow rate versus RAFR (HFK'ye göre toplam ısı girişi ve yakıtın kütlesel debisinin değişimi)

The advantages of ethanol as an alternative fuel in an SI engine in the thermal efficiency and energy consumption can be seen in Fig. 7. An approximately 3.3% increase in brake thermal efficiency and a 3.2% decrease in BSEC were obtained using E85 considering all experimental data.

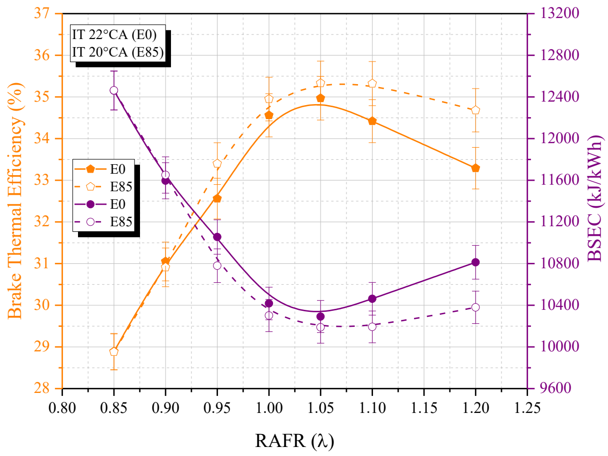

Figure 7. The variation of the brake thermal efficiency and BSEC versus RAFR (HFK'ye göre fren termik verimi ve FÖET'nin değişimi)

In Fig. 2, the emission amount in ppm is used in the comparison of both fuels; however, the specific NO emission can be used to provide more meaning to the obtained emission values. For this purpose, the empirical Eq. (6), which was also used in the studies in the literature [62-65], was used.

$$EP_i = EV_i \times \left(\frac{M_i}{M_{exh}} \times \frac{\dot{m}_{exh}}{P_e} \right) \qquad (6)$$

where EP_i, EV_i, M_i, M_{exh}, $\dot{m}_{exh}$, and P_e refer to the pollutant mass (g/kWh), exhaust emission value of the components (ppm), mol mass of the components (kg/kmol), mol mass of the exhaust (kg/kmol), exhaust mass flow (kg/h), and power output (kW), respectively.

Fig. 8 illustrates the variations of BSNO. When Fig. 2 and 8 are compared to each other, it can be seen that the variation of BSNO as g/kWh changes similar to that of NO. When the NO emission emitted from the engine is defined to correspond to how much power the engine produces, it can also be seen that E85 has an advantage. Because of improvement in the NO emission and engine power, BSNO was obtained lesser for E85. Especially when considering 1.05 or 1.1 RAFRs, where NO emission reached the highest value, BSNO decreased by an average of 38.4%.

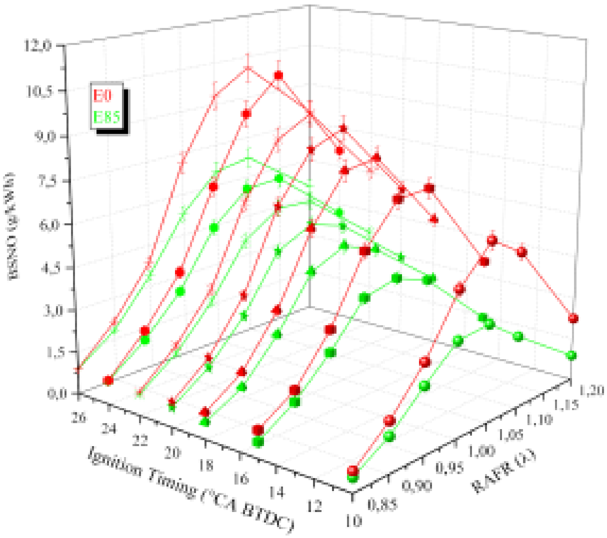

Figure 8. The variation of the BSNO emission depending on RAFR and ignition timing (Ateşleme zamanı ve HFK'ye bağlı olarak özgül NO emisyonunun değişimi)

4. CONCLUSIONS (SONUÇLAR)

The results obtained in this study, which compared the effects of E85 and gasoline on NO emissions, considering the ignition timing and RAFR parameters, are summarized as follows:

- The engine output power obtained using E85 was similar to or greater than that of E0.
- When all experimental data obtained with E0 and E85 were compared to each other, it was seen that gravimetric fuel consumption and BSFC were increased on average by 39.3% and 37.5%, respectively. Especially, the lower heating value and stoichiometric air/fuel ratio of ethanol may be considered a reason for this result. However, considering all data each other, brake thermal efficiency increased by an average of 3.3% and BSEC decreased by an average of 3.2% with E85.
- The exhaust gas temperatures for E85 decreased by an average of 22.6 °C, compared to E0. Higher laminar burning velocity and lower adiabatic flame temperature of ethanol could be effective in this result.
- Significant differences were obtained between in values BSNO between gasoline and E85. Considering the maximum NO point of 1.05 or 1.1 RAFRs, a 38.4% reduction in BSNO was obtained.

Conventional vehicles with ICE have been evolving into hybrid, fully electric, or fuel cell vehicles recently. In this transformation period, the power and energy sources of hybrid vehicles are important for the ecosystem and human beings. In this respect, it can be predicted that studies on the use of alternative fuels such as ethanol for SI engines will continue to be important, especially in hybrid vehicles.

DECLARATION OF ETHICAL STANDARDS
(ETİK STANDARTLARIN BEYANI)

The authors of this article declares that the materials and methods they use in their work do not require ethical committee approval and/or legal-specific permission.

Bu makalenin yazarları çalışmalarında kullandıkları materyal ve yöntemlerin etik kurul izni ve/veya yasal-özel bir izin gerektirmediğini beyan ederler.

AUTHORS' CONTRIBUTIONS (YAZARLARIN KATKILARI)

***Mustafa Ceyhun ERKOCA*:** He conducted the experiments, analyzed the results, and performed the writing process.

Deneyleri yaptı, sonuçları analiz etti ve makalenin yazma sürecini gerçekleştirdi.

Tolga TOPGÜL: He carried out the methodology of the study, followed the experiments, analyzed the results, and performed the writing process.

Çalışmanın metodolojisini yürüttü, deneyleri takip etti, sonuçları analiz etti ve makalenin yazma sürecini gerçekleştirdi.

CONFLICT OF INTEREST (ÇIKAR ÇATIŞMASI)

There is no conflict of interest in this study.

Bu çalışmada herhangi bir çıkar çatışması yoktur.

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