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The Effect of Using Amyl Alcohol in a Diesel Engine on Performance and Emission Parameters

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Abstract

In this study, experimental tests were carried out to improve the performance and emission characteristics of the diesel engine as amyl alcohol (pentanol), which is in the heavy alcohol class, obtained from the residual waste from ethanol, which is produced as a by-product during sugar production from sugar beet. Tests were performed on naturally aspirated, air-cooled, four-stroke, single cylinder, direct injection, 6LD 400 Antor diesel engine at full load and engine speeds of 1400, 1700, 2000, 2300, 2600, 2900 and 3200 rpm. Pure diesel and fuel mixtures containing 5%, 10% and 20% amyl alcohol were used in the experiments. As a result of the experiments, while the power and torque values decreased, the brake specific fuel consumption (BSFC) value increased as the ratio of amyl alcohol in the mixture increased compared to diesel fuel. In addition, the increase in amyl alcohol ratio in the mixture decreased hydrocarbon (HC), carbon monoxide (CO), and smoke emissions, while increasing carbon dioxide (CO2) and nitrogen oxide (NOx) emissions. With 20% amyl alcohol ratio, an increase of 30.324% in BSFC value and a decrease of 13.745% and 10.258% in power and torque values were found as the average of all speeds, respectively. When evaluated in terms of emissions, with 20% amyl alcohol ratio, an average reduction of 44.565%, 42.832% and 27.330% was achieved in HC, CO, and smoke emissions, respectively, while NOx and CO2 emissions in-creased by 15.520% and 54.934%, respectively.

Keywords: Amyl alcohol, Performance, Emission, Diesel engine

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1. Introduction

The importance of energy, which is one of the basic elements of life, increases with the rising in population and the acceleration of urban and industrial transformation in parallel with this increase [1–3]. The limited fossil-based fuel reserves, which have an important share in meeting the energy needs, create a fragile structure for the world economy [4–6]. Subsequent oil crises and related price increases have led countries to search differently [7,8]. In addition, the rate of polluting emissions such as CO_2, HC, and NO_x, which cause global warming because of excessive consumption of fossil-based fuels, is increasing day by day. The fact that polluting emissions constitute a major problem for the environment and human health, and that fossil fuels are the source of such problems have made it necessary for researchers to work on renewable energy sources [9–12].

Studies have focused on alternative energy sources that emit fewer polluting emissions compared to fossil-based fuels [13]. The most suitable alternative to fossil-based fuels is biodiesel and bio alcohols, which are described as biofuels [14,15]. Bio alcohols are generally obtained by subjecting plant wastes to biomass energy conversion processes. Plants containing sugar and starch are particularly preferred in alcohol production. The raw material is put into the fermentation process and then it is purified from water and similar by-products by the distillation method to obtain alcohol [16]. It is possible to use the obtained alcohol as fuel in internal combustion engines [17]. Alcohols shown with the general formulation of $C_nH_{2n} + 2O$ contain oxygen in their structures. Their oxygen content improves the combustion reaction in the cylinder and contributes to the improvement of exhaust emissions. In addition, improving the combustion efficiency of alcohol allows the engine to run stable.

There are many studies on the effects of alcohol use in combination with diesel on engine performance and exhaust emissions in internal combustion engines. Ozdalyan [18] aimed to measure the n-butanol and diesel fuel mixtures effect of on exhaust emissions at different injection pressures. Improvements in emissions (CO, smoke and NO_x) were detected with the increase of n-butanol in the mixture. In a different study, Sayin [19] examined the effects of diesel-ethanol (5-10% ethanol + 95-90% diesel) and diesel-methanol (5-10% methanol + 95-90% diesel) test mixtures on engine responses. According to these data; reductions in HC, CO, smoke emissions and BTE have been detected. In addition, it has been demonstrated that BSFC and NO_x emissions have increased. In the study on the effects of fusel oil on engine performance and emission data conducted by Agbulut et al. [20], the effects of F20 (20% fusel oil + 80% diesel) fuel mixture and F0 (100% diesel) reference fuel were compared. It was concluded that the BSFC increased due to the lower calorific value of fusel oil compared to diesel fuel. On the other hand, an increase in CO_2 and a decrease in NO_x in exhaust emissions were detected. In the study conducted by Yılmaz [21], experiments were conducted at different engine loads with test fuels created using fusel oil. The BSFC increased with the increase in the proportion of fusel oil in the test fuel. In addition, a decrease in the in-cylinder pressure value was measured due to the water and oxygen the fusel contains. There has been an increase in CO emissions due to the negative impact of water content on combustion. In addition, NO_x emissions have decreased due to the low thermal value of fusel oil. There are other studies on alcohols such as butanol, methanol, ethanol and fusel oil [22–27].

Fusel oil is a natural source of 2 to 5 carbon straight and chain monohydric alcohols. At the stages in which ethyl alcohol is produced, it appears as ethyl alcohol residue. It consists of i-amyl, i-butyl and n-propyl alcohols, ethyl alcohol and water, which are formed during fermentation [28]. Fusel oil is used as one of the by-products of the distillation step in producing alcohol and is the natural source of amyl alcohol. Iso-amyl-alcohol is obtained by 2 distillation of fusel oil [29].

In previous studies, many studies were found on blends of fusel oil and diesel fuel. However, it has been observed that studies on amyl alcohol obtained by passing fusel oil through various processes (distillation, etc.) are limited. In this study, the use of amyl alcohol, which is detected in the content of fusel oil and classified as heavy alcohol, as an alternative fuel in a single cylinder diesel engine was evaluated. Engine performance and exhaust emission data obtained from test fuels formed with amyl alcohol were compared with diesel, our reference fuel.

2. Material and method

2.2 Test fuels

The tests are carried out with different proportions of Amyl alcohol-Diesel mixtures, A5 (5% Amyl alcohol + 95% Diesel), A10 (10% Amyl alcohol + 90% Diesel) and A20 (20% Amyl alcohol + 80% Diesel) and A0 (pure diesel). Four fuels used in this study were kept at room temperature in the laboratory for 76 hours. No phase change was observed during the holding period. Many properties of amyl alcohol and diesel fuel mixtures such as density, lower calorific value, and upper calorific value have been analyzed by TUBITAK Marmara Research Center. The properties of the test fuels are given in Table 1 and the fuel properties of the diesel and binary blend fuels are given in Table 2.

2.1 Experimental setup

In this study, a naturally aspirated, air-cooled, single cylinder, four-stroke, direct injection ANTOR 6LD 400 diesel engine with a compression ratio of 18:1 and a cylinder volume of 395 cm^3 was used. Figure 1 shows the experimental setup of the engine and other equipment used in this study, and Table 3 shows the technical characteristics of the test engine. The data were recorded on the test engine using TFX Engineering DAQ system consisting of dynamometer, torque, speed sensor, oil temperature sensor and fuel measurement sensor. The temperature of the ambient air and the temperature of the exhaust gas emission were measured using K type thermocouples collected by the data logger of the Pico thermocouples. While thermocouples were placed in the air metering unit and the exhaust manifold, the emissions were measured using a separate unit of the Bilsa MOD 2210 WINXP-K exhaust gas analyzers. The experiments have been measured at 300 rpm intervals, between 1400 and 3200 rpm. During the tests, no changes were made to the engine's original injection pressure and compression ratio. In the tests, the engine was run until it reached operating temperature. To prevent cold start effects, the engine was run on pure diesel for about fifteen minutes before the fuel tank containing the fuel blends was used. Tests were carried out under steady conditions and experiments with pure diesel were started to obtain basic data of the engine. In this study, BSFC, engine power, torque, and emissions (HC, CO, CO_2, $NO_{x,}$ and smoke) were investigated.

Table 1. Technical characteristics of the test engine

	D100	**A100**	**Analysis compliant to**
CAS Number	68334-30-5	71-41-0	
Chemical Formula	$C_{13}H_{18}$	$C_5H_{12}O$	
Molecular Weight (g/mol)	184.3613	88.1482	(Calculated)
Kinematic Viscosity at 40 ℃ (mm^2/s)	4.24	3.68	EN ISO 3104
Higher Calorific Value (MJ/kg)	46.105	38.26	ASTM D 240
Lower Calorific Value (MJ/kg)	43.199	35.35	(Calculated)
Latent heat of evaporation (kJ/kg)	260	308	ASTM D 240
Density at 15 °C (kg/m^3)	883.5	810.5	EN ISO 12185
Sulphated Ash Content % (m/m)	0.0016	-	TS 1965
Cold Filter Plugging Point °C	-13.89	-	TS EN 116
Sulphur (mg/kg)	5.5	-	TS EN ISO 20646
Flashing Point (°C)	174	47	ASTM D 92
Freezing Point (°C)	-15	-117.3	ASTM D 97
Number of Cetanes	54	20	EN ISO 5165

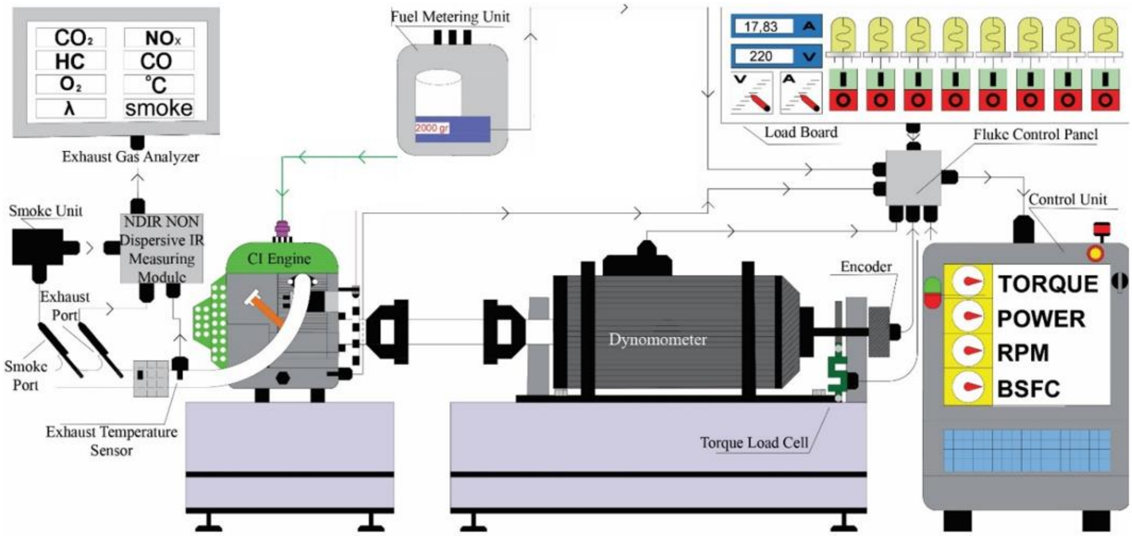

Fig. 1. Schematic view of experimental design

Table 2. Fuel properties of the diesel and binary blend fuels.

	D100	A5	A10	A20	Analysis compliant to
Kinematic Viscosity at 40 °C (mm^2/s)	4.24	4.212	4.184	4.128	EN ISO 3104
Lower Calorific Value (MJ/kg)	43.199	42.807	42.414	41.629	(Calculated)
Density at 15 °C (kg/m^3)	883.5	879.85	876.2	868.9	EN ISO 12185
Number of Cetanes	54	52.3	50.6	47.2	EN ISO 5165
Oxygen Content (wt.%)	0	0.9075	1.815	3.63	

Table 3. Technical characteristics of the test engine

Brand	Antor / 6LD400
Cylinder	1
Displacement (cm^3)	395
Bore (mm)	86
Stroke (mm)	68
Compression Ratio	18:1
Maximum power (kW)	5.4 @ 3000 rpm
Maximum torque [Nm]	19.6 @ 2200 rpm
Injection nozzle	0.24 [mm] x 4 holes x 160 °
Nozzle opening pressure [bar]	180
Fuel delivery advance angle [°CA]	24 ° before top dead center

The measured values of the uncertainty of the different variables are shown in Table 4. The overall uncertainty was calculated as follows:

$$\begin{aligned} &Overall\ uncertainty \\ &= square\ root\ of\ [(uncertaint\ of\ speed)^2 \\ &+ (uncertaint\ of\ Power)^2 \\ &+\ (uncertaint\ of\ Torque)^2 \\ &+\ (uncertaint\ of\ BSFC)^2 + (uncertaint\ of\ HC)^2 \\ &+ (uncertaint\ of\ CO)^2 + (uncertaint\ of\ CO_2)^2 \\ &+\ (uncertaint\ of\ NO_x)^2 \\ &+\ (uncertaint\ of\ smoke)^2] \end{aligned}$$

$$\begin{aligned} = \boldsymbol{square\ root\ of}\ &[(\mathbf{0.25})^2 + (\mathbf{1.50})^2 + (\mathbf{1.8})^2 \\ &+ (\mathbf{1.25})^2 + (\mathbf{1.9})^2 + (\mathbf{2.1})^2 \\ &+ (\mathbf{1.75})^2 + (\mathbf{2.45})^2 + (\mathbf{1.55})^2] \\ &= \pm\mathbf{5.158}\ \% \end{aligned}$$

Table 4. Uncertainty of the variables

Measurement Items	Percentage Uncertainty
Speed measurement	±0.25
Power	±1.50
Torque	±1.80
BSFC	±1.25
HC	±1.90
CO	±2.10
CO_2	±1.75
NO_x	±2.45
Smoke	±1.55

3. Results and Discussions

The changes of engine powers and engine torques of A0, A5, A10 and A20 fuels depending on engine speed are shown in Fig. 2 and Fig. 3, respectively. Maximum engine power was obtained as 2.60 kW at 3200 rpm engine speed with A0 fuel. With the use of A5, A10 and A20 fuels at this engine speed, a decrease of 15%, 15.769% and 17.307% was observed in engine power compared to A0 fuel, respectively. Since the lower calorific value of amyl alcohol is lower than diesel fuel, amyl alcohol diesel fuel mixtures have lower energy content and therefore engine power is thought to be lower than diesel fuel. Moreover, since the latent heat of vaporization of amyl alcohol is higher than diesel, it negatively affects the combustion efficiency, so the power and torque values are negatively affected with the increasing amyl alcohol ratio in the mixture. Maximum engine torques for A0, A5, A10 and A20 fuels were obtained at an engine speed of 2600 rpm. According to A0 at 2600 rpm engine speed; With the use of A5, A10 and A20 fuels, engine torque decreased by 5.900%, 3.540% and 5.457%, respectively.

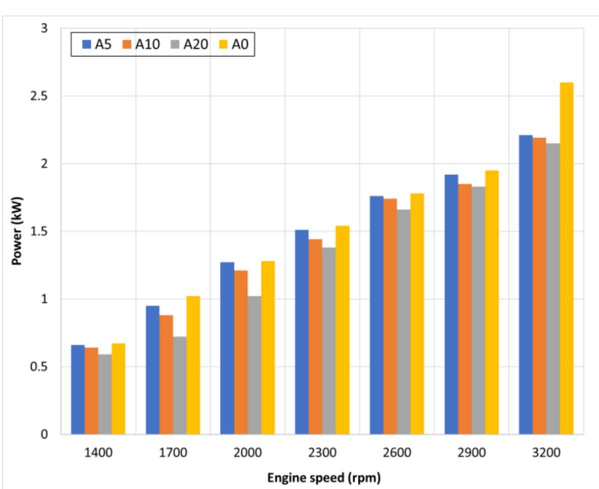

Fig. 2. Power values of test fuels depending on engine speed

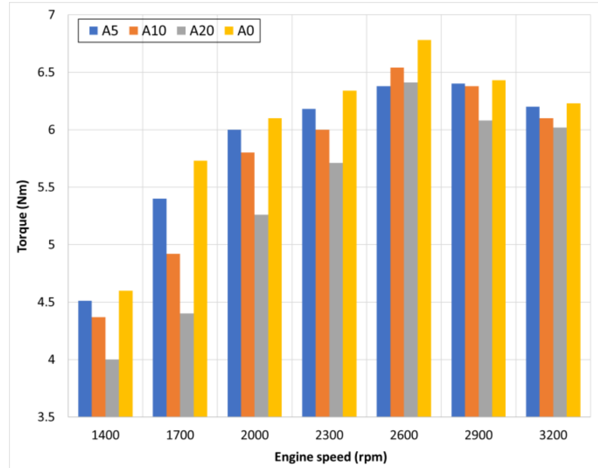

Fig. 3. Torque values of test fuels depending on engine speed

In Fig. 4, BSFC changes of different fuels can be seen depending on the engine speed. Minimum BSFC was seen at 2300 rpm engine speed for all fuels. With the use of A5, A10 and A20 fuels at 2300 rpm engine speed, the BSFC values increased by 2.630%, 32.174% and 70.280%, respectively, compared to diesel fuel. If the same volume of diesel and amyl alcohol / diesel fuel mixtures are sprayed into the cylinder, diesel will release a higher amount of energy. Therefore, since amyl alcohol / diesel fuel mixtures have lower cetane number and lower thermal values than diesel, it is necessary to use more amyl alcohol / diesel fuel mixtures in mass to achieve the same effective power compared to diesel.

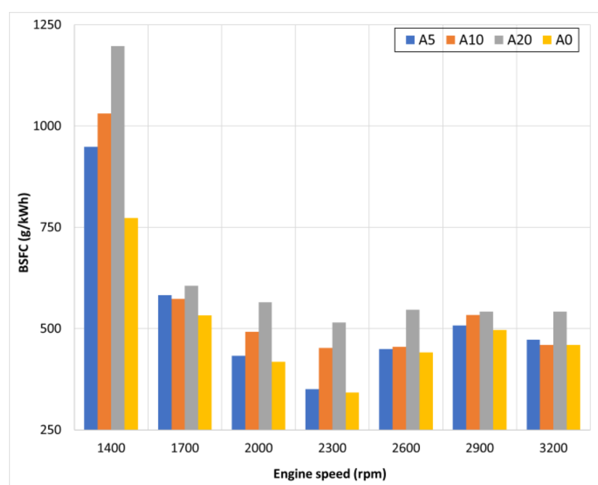

Fig. 4. BSFC values of test fuels depending on engine speed

Incomplete combustion is the main cause of both CO and HC emissions [30]. Fig. 5 and Fig. 6 show changes in HC and CO emission, depending on the engine speed, respectively. HC emission decreased as engine speed increased. The decrease in HC emission can be explained by the increase in cylinder temperature with the increase of engine speed and the increase in combustion efficiency because of the impoverishment effect of amyl alcohol. Compared to the reference fuel A0 at 3200 rpm engine speed, the HC emissions of A5, A10 and A20 fuels decreased by 23.809%, 52.380% and 57.147%, respectively. On the other hand, according to the reference fuel A0 fuel; CO emissions of A5, A10 and A20 fuels decreased on average by 20.207%, 30.397% and 42.832%, respectively. Amyl alcohol contains less carbon than diesel fuel, the oxygen content increases with the increase of amyl alcohol ratio in amyl alcohol and diesel mixtures, and the low stoichiometric air-fuel ratio of amyl alcohol causes an impoverishment effect of diesel fuel amyl alcohol mixtures, resulting in reduced CO emissions. Although the high latent heat of evaporation of amyl alcohol adversely affected the combustion efficiency, thanks to the high oxygen and low carbon ratio it contains the incomplete combustion product HC and CO decreased.

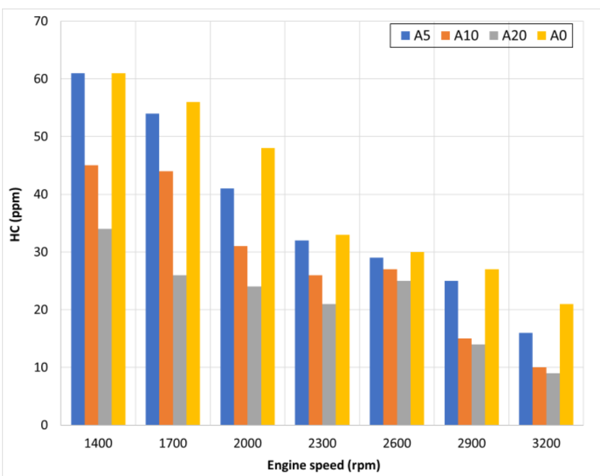

Fig. 5. HC emissions of test fuels depending on engine speed

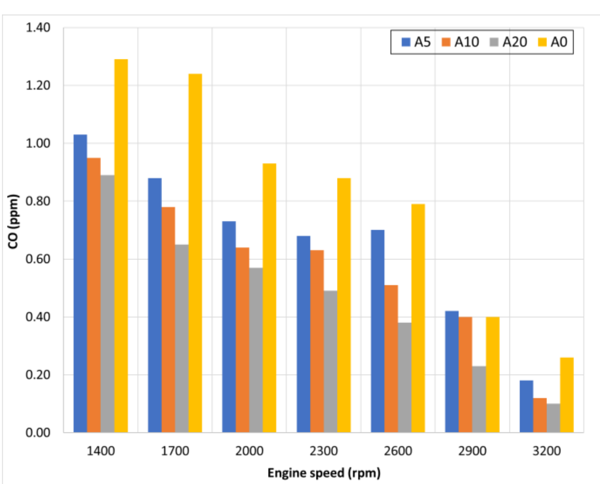

Fig. 6. CO emissions of test fuels depending on engine speed

In Figure 7, the change of CO_2 emission according to the engine speed is given for the test fuel and test fuel mixtures. As can be seen in the figure, CO_2 emission increased with increasing engine speed, and fuel blends (A5, A10 and A20) gave higher CO_2 emission values than the A0 reference fuel. The increase in CO_2 emissions with engine speed is the result of more fuel entering the cylinder. According to A0 at 3200 rpm engine speed, CO_2 emissions of A5, A10 and A20 fuels increased by 5.376%, 22.401% and 39.068%, respectively. Figure 8 shows the changes of NO_x emissions depending on the increase in engine speed. NO_x emissions reached their maximum value at 3200 rpm engine speed. With the increase of engine speed, especially at high engine speeds, NO_x emissions increased with the addition of amyl alcohol compared to diesel fuel. At 3200 rpm engine speed according to A0; NO_x emissions of A5, A10 and A20 fuels increased by 2.532%, 9.580% and 11.220%, respectively. It is estimated that the increase in NO_x emissions with the use of amyl alcohol compared to diesel fuel is due to the oxygen in amyl alcohol. Additionally, as the alcohol ratio increases, the ignition delay increases due to the decreasing cetane number and this increases the combustion temperature. Increasing combustion temperatures also cause an increase in NO_x emissions. Although the high latent heat of vaporization of amyl alcohol causes lower flame temperatures, NO_x emissions have increased due to the oxygen it contains and the low cetane number. In addition, the increase in cylinder temperature together with the increasing engine speed triggered the increase of NO_x emissions.

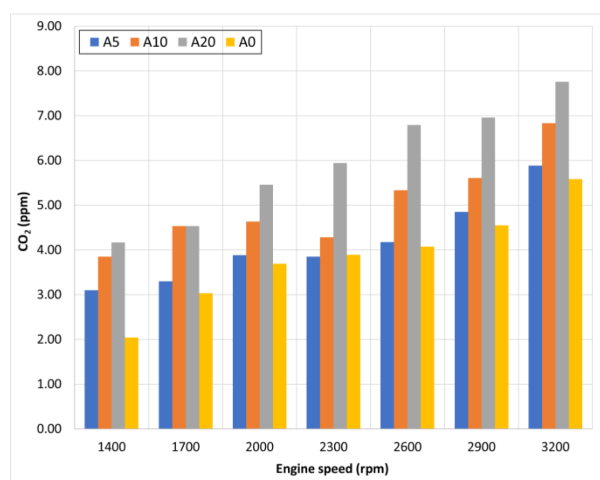

Fig. 7. CO_2 emissions of test fuels depending on engine speed

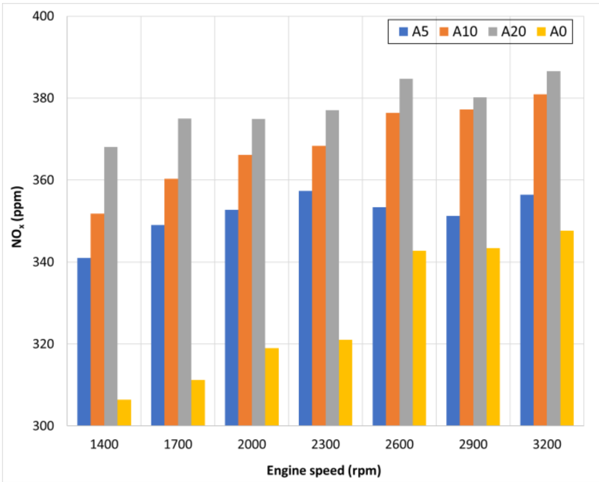

Fig. 8. NO_x emissions of test fuels depending on engine speed

Fig. 9 shows the graph of smoke emissions of fuel mixtures with amyl alcohol addiction and diesel fuel. The rate of smoke emissions decreases as the ratio of amyl alcohol increases in the fuel. Minimum smoke emission occurs at an engine speed of 3200 rpm. At 3200 rpm engine speed, compared to A0, smoke emissions of A5, A10 and A20 fuels decreased by 10.769%, 35.385% and 38.462%, respectively. It is thought that by improving the viscosity and density by adding amyl alcohol to the fuel, smoke emissions are reduced. Improving viscosity and density positively affects fuel atomization and combustion quality. Thus, the oxidation temperature of smoke particles formed during the combustion process decreases and as a result, there is a decrease in smoke emissions. Moreover, the presence of oxygen in the structure of amyl alcohol also reduced smoke emissions. This reduction increased with increasing amyl alcohol ratio.

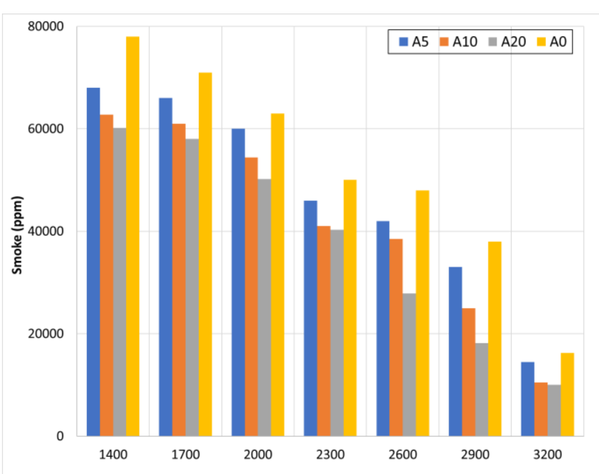

Fig. 9. Smoke emissions of test fuels depending on engine speed

4. Conclusions

The most important features preferred in alternative fuels used in diesel engines are that they are economically convenient and can be used without any structural changes on the engine. In this experimental study, the usability of amyl alcohol-diesel fuel mixtures in diesel engine was tested. The effect of 5%, 10% and 20% amyl alcohol addition to diesel fuel on engine performance and emissions was examined in a single cylinder direct injection diesel engine and the following results were obtained;

- ✓ With the addition of amyl alcohol to diesel fuel, engine torque and engine power decreased. According to the reference fuel A0, a decrease in engine torque with A5, A10 and A20 fuels by an average of 2.700%, 4.975% and 11.158% was found, respectively, while a decrease of 5.166%, 8.210% and 13.745% was observed in the engine power, respectively.

- ✓ Compared to the A0 reference fuel, the BSFC value increased by an average of 8.086%, 15.370% and 31.487%, respectively, with the use of A5, A10 and A20 fuels.

- ✓ Compared to the reference fuel A0 fuel, the CO emissions of A5, A10 and A20 fuels decreased on average by 20.207%, 30.397% and 42.832%, respectively.

- ✓ In comparison to the reference fuel A0, the HC emission decreased by 6.521%, 28.260% and 44.565% on average with A5, A10 and A20 fuels, respectively.

- ✓ According to the A0 fuel, the CO_2 emissions of A5, A10 and A20 fuels increased by 8.119%, 30.577% and 54.934%, respectively.

- ✓ NO_x emission values obtained from A5, A10 and A20 fuels increased on average by 7.460%, 12.643% and 15.502%, respectively, compared to A0 fuel.

- ✓ The smoke emissions of A5, A10 and A20 fuels decreased on average by 9.540%, 19.519% and 2.330%, respectively, compared to A0 fuel.

When the results obtained from the experimental study are examined, the data that coincide with the previous research results in the literature were obtained. It has been demonstrated in the literature that fuels with high oxygen content increase the combustion efficiency and contributes to the improvement of some exhaust emissions. The addition of oxygen-containing amyl alcohol to diesel fuel reduced CO, smoke and HC emissions, while slightly increasing NO_x and CO_2 emissions. While a decrease in power and torque was detected with the addition of amyl alcohol, an increase occurred in the values of specific fuel consumption. As a result, it has been demonstrated that isoamyl alcohol can be used as fuel in diesel engines without any engine modification.

Conflict of Interest Statement

The authors declare that there is no conflict of interest.

CRediT Author Statement

Suleyman Simsek: Conceptualization, Supervision, **Samet Uslu:** Conceptualization, Writing-original draft, Validation

Nomenclature

A0	:	*100% Diesel*
A5	:	*5% Amyl alcohol + 95% Diesel*
A10	:	*10% Amyl alcohol + 90% Diesel*
A20	:	*20% Amyl alcohol + 80% Diesel*
BSFC	:	*Brake specific fuel consumption*
CO	:	*Carbon monoxide*
CO_2	:	*Carbon dioxide*
HC	:	*Hydrocarbon*
NO_x	:	*Nitrogen oxide*

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