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A Comparative Study of Ethanol and Methanol Addition Effects on Engine Performance, Combustion and Emissions in the SI Engine

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Abstract

In this study, the availability of methanol instead of ethanol was investigated in terms of performance, emission and combustion characteristics. The experiments were conducted in a single cylinder, four-stroke SI engine for different engine speeds at full engine load. Test fuels were prepared by 10% ethanol and methanol addition into gasoline. According to the experimental results, while methanol addition increased bsfc values by 10.3% compared to ethanol addition, it caused a reduction to the bte values by 6.12%. The methanol addition fuel has shown similar combustion characteristics with ethanol addition fuel. Although the methanol addition decreased CO_2, CO, HC and NOx emissions by 6.48%, 26.6%, 4.75% and 9.16% respectively compared to ethanol addition, it has higher oxygen emission values by 15.3% due to its higher oxygen content than ethanol. These results show that methanol can also use as an additive for gasoline like ethanol.

Keywords: Combustion characteristics; Ethanol; Exhaust emissions; Methanol; SI engine

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1. Introduction

Transportation sector is one of the areas where energy is most needed, and almost all of vehicle used in this sector have an internal combustion engine. These engines have been more popular for applications requiring power owing to the high power supply, efficiency and reliability. Among the internal combustion engines, spark ignition (SI) engines have most commonly used for fast road transport owing to low harmful gas release and high power. However, spark ignition engines have higher fuel consumption, lower efficiency, limited range of fuel options according to diesel engines [1-2].

In recent years, energy consumption and demand have increased due to the rapid growth of population, developments in technology and industry. This causes the consumption of petrol based fuels to increase with each passing day on the world. Thus, petrol reserves are decreasing besides, major problems such as air pollution, global warming, deterioration of human health, damages on environmental and ecosystem were also began rise by use of these fuels. Therefore, the academic societies in many developed countries have increased researches on the clean energy. Furthermore, important agreements such as International United Nations Framework Convention on Climate Change, Vienna Convention for the Protection of the Ozone Layer, Convention on Long-Range Transboundary Air Pollution, and Kyoto protocol have been accepted by many countries [3-5]. Therefore, researchers are investigating the alternative fuels which can improve the performance parameters and emission characteristics. These alternative fuels must have got renewable, sustainable, cheap and environmentalist.

There is a strong working to development of alternative fuels usable in SI engines on worldwide. The most prominent alternative fuels for SI engines are alcohols obtained from biomass put forward of researchers. Specifically, ethanol and methanol produced with biomass from municipal solid waste and non-edible cultivated resources are being increasingly explored [6-7]. Ethanol has similar fuel and combustion properties with gasoline. Therefore, it is observed to be an important fuel suitable for use in SI engines [8-10]. High octane number (approximately 102) of the ethanol provides opportunity the use at higher compression ratios for better efficiency and performance [11]. The combustion efficiency increases thanks to its content of oxygen [12-13], and thus, it decreases harmful exhaust gas emissions.

Some important studies on using in SI engines of ethanol in literature have presented below.

Qian et al., in their studies, have used investigated effects on combustion and emission characteristics of ethanol addition (21%, 25%, 29%, 32% and 35% as volumetric) in gasoline as fuel in a SI engine. As test results, they presented that increase of ethanol ratio in fuels causes a decrease for both maximum cylinder pressure and maximum heat release rate (HRR) values. Besides, flame development duration and rapid combustion duration have also increased. When exhaust emission parameters are investigated, while CO emissions increased, NOx and HC emission values decreased [14]. Zaharin et al. have presented to effects on performance and emission parameters of gasoline-ethanol blend (10% as vol.) as a SI engine fuel. They reported that engine power increased by average 7.71%, brake specific fuel consumption (bsfc) improved in 3.57%, brake thermal efficiency (bte) increased by 7.36%, exhaust gas temperature increased by approximately 4.5% as engine performance parameters. Besides, ethanol addition has decreased CO and HC emissions by 7.08% and 6.59% respectively, and it has increased CO_2 and NOx emissions by 7.64% and 8% respectively [15]. Chansauria and Mandloi have investigated effects of ethanol addition 5% and 10% inside gasoline on a vehicle. As results, it observed that ethanol has caused an increment in the bte and HRR, a reduction in the cylinder pressure at low load, and also increase at high load. Besides, bsfc values have increased with ethanol addition [16]. Deng et al., have presented a study on performance and emissions of hydrous ethanol-gasoline blends in a four-cylinders aSI engine. They have determined fuel blends which are containing 10% and 20% ethanol as vol. According to results of their study, the highest torque and power values have obtained with fuel which is 10% ethanol contain. But, increment of ethanol ratio has caused a slightly reduction of them. The bsfc and the bte also increased in general with using of ethanol. On the other hand, while CO and HC emissions decreased significantly, an increment has observed in NOx emissions [17]. Yusoff et al., have also investigated effects of ethanol addition 10% and 20% into gasoline in a four-cylinders and multi-point fuel injection system SI engine. Engine torque, power and bte increased up to 3.88%, 6.71% respectively with 20% ethanol fuel, and the bsfc decreased by 4.83% with it. Although CO and HC emissions decreased up to12.2% and 13.71% with ethanol addition, CO_2 and NOx values increased up to 1.23% and 1.58% [18]. Balki et al., in their study, have used pure ethanol as fuel, and compared torque, bsfc, HC and CO_2 values with that of gasoline. They reported that with using of gasoline as fuel, max torque was 11.1 Nm, min bsfc was 278.8 g/kWh, max HC emission was 196 ppm, max CO_2 was 13.7%, on the other hand, with pure ethanol, max torque was 11.41 Nm, min bsfc was 453.7 g/kWh, max HC emission was 115 ppm, max CO_2 was 13.2% [19].

The methanol is a short chain alcohol that can be produced from both renewable and fossil feedstock (natural gas, coal, wood, agricultural and municipal waste, etc.). Methanol has chemical formula CH_3OH, and its H/C ratio is higher according to the known fuels. Besides, the methanol has also high oxygen content and high octane number like ethanol. Its high oxygen content provides better combustion. Low-combustion temperature causes a reduce in the heat transfer loss, moreover the compression losses decreased thanks to the high latent heat of vaporization, thus, both resulting in higher engine efficiency [20-22].

Although methanol is suitable for SI engines as fuel, there are a few studies on the use of methanol in SI engines in literature.

Özcan and Çakmak, in their study, have put forth that 10% methanol-gasoline blend increased power and bsfc values by 7.76% and by 18.65% respectively according to gasoline. Besides, methanol has also caused increase of max cylinder pressure value [23]. Poran and Tartakovsky have investigated effects on performance and emission characteristics of methanol steam injected into intake manifold of a single cylinder SI engine. They have shown that methanol increased thermal efficiency by 18%, improved CO, HC and NOx emissions up to 90%, 85% and 73% respectively [24]. Elfasakhany has added by 3, 7 and 10% methanol in gasoline, and has investigated effects on performance and emissions of a single cylinder SI engine. Experimental results shown that methanol increased average up to 2.1%, 3.9% and 33%, respectively, engine torque, power and volumetric efficiency compared to gasoline. On other hand, while CO and HC emissions have decreased up to 28.5% and 12.8% respectively, CO_2 emission has decreased up to 8.2% according to gasoline [25].

Although especially ethanol is used as fuel at many regions on the world, the using of the methanol in SI engines is not yet widespread. Many researchers, some of whom are also mentioned above, stated that adding 10% ethanol into gasoline increases engine performance and reduces emissions. Ethanol cannot be stored for long periods of time, and after contact with oxygen, it starts to be watered or methylated. Therefore, methanol can be an alternative fuel to ethanol. In addition, methanol is an easy producible and abundant alcohol. In order to increase the effective use of methanol in SI engines, the effects of adding 10% ethanol and methanol into gasoline on performance, emission and combustion parameters were investigated in this study.

2. Experimental Setup and Procedures

The experimental setup has occurred from a single cylinder SI engine, an electric dynamometer, combustion analysis equipment and gas analyzer. Tests have conducted under different engine speeds at full throttle according to full load experiment method. The test engine is produced special for experimental studies. It has variable compression ratios and ignition times. Although the running range of engine is 1600-3400 rpm, the speed range for running at steady state of engine was determined as 2100-3200 rpm, and therefore, tests were conducted between of these speeds.

2.1.Engine Experiment Setup and Test Method

In the experiments, a four-stroke, single cylinder and air cooled SI engine was used. The technical specifications of SI engine used at experiments are presented in Table 1. Figure 1 shows the schematic view of test setup.

Fig. 1. The experimental test setup

Fuel consumption was measured with a scaled tube as volumetric. The bsfc was also calculated via equation 1.

$$bsfc = \frac{\dot{m}_f.3600}{P_e}, g/kWh \quad (1)$$

Here, $\dot{m}_f$ is fuel consumption (g/s) as mass, P_e is effective engine power (kW). The equation 2 was used for calculation of the bte value.

$$bte = \frac{P_e}{\dot{m}_f.H_u}, \% \quad (2)$$

Here, H_u refers to lower heating value (LHV) in MJ/kg of fuel. The bte denotes transformation amount to useful work of fuel. Therefore, LHV is a very important parameter for fuels.

Table 1. The technical specifications of test engine

Model	Gunt CT 152
Type	Four-Stroke, Carbureted
Cylinder	Single
Sweeping volume	0.148 L
Diameter x Stroke	65.1 x 44.4 mm
Cooling system	Air cooled
Max power	1.2 kW
Max torque	4.5 Nm
Compression rate	7:1

An electronic controlled dynamometer for torque measurement and loading of engine was used which it has 6 kW power and 8000 rpm engine speed values. Engine speed and engine torque values can be both seen instantly and recorded with a data-logger. The air consumption was measured to keep the air/fuel ratio at a constant value with orifice plate and difference pressure transducer. Besides, exhaust gas temperature, fuel temperature, aspired air temperature and ambient temperature were measured via thermocouples. The all values can be seeming on control unit of dynamometer. A thermocouple and data logger were also used for the engine surface temperature.

2.2.Gas Analyzer and Emission Tests

Mobydick 5000 brand gas analyzer was used for analyses of exhaust gases. The exhaust gas analyzer can measure HC (ppm), CO (% vol), O_2 (%vol), CO_2 (%vol) and NOx (ppm) gases. The technical specifications of gas analyzer are presented in Table 2. The probe of gas analyzer was coupled to exhaust manifold directly for accuracy measurement of exhaust gases.

Table 2. The technical specifications of gas analyzer

Gases	Measuring Ranges	Accuracy
CO	0-10, %	0.01
CO_2	0-20, %	0.01
HC	0-2000, ppm	1
O_2	0-21, %	0.01
NOx	0-5000, ppm	1

2.3.Combustion Analysis Equipment and Method

Combustion analyze equipment used in experiments was occurred from a Kistler - 6118C model piezoelectric pressure transducer (for pressure measurement) which has 0-200 bar measurement range and 10.29 pC/bar sensitivy, and the Kistler - 5018A brand amplifier (for signal strengthening), and Atek-ARC S 50 model incremental encoder (for top dead point detection and measurement of crank angle) which has max 6000 rpm working speed and 300 kHz output frequency. Besides, the analog signals generated from pressure transducer were converted to digital signals via National Instrument-USB 6210 model data logger.

The cylinder pressure data were calculated by averaging of 100 consecutive cycles in succession. The crank angle dependent changes of cylinder pressure data were prepared via a specific algorithm made in LabVIEW. The HRR values were calculated by the following equation 3 with the one-dimensional combustion model using the first law of thermodynamics.

$$\frac{dQ_{net}}{d\theta} = \frac{\gamma}{\gamma-1} P \frac{dV}{d\theta} + \frac{1}{\gamma-1} V \frac{dP}{d\theta} \quad (3)$$

Here, dQ_{net} refers to the energy transfer value on the cylinder walls; γ refers to the specific heat rate; θ is the crank angle (CA); V refers to the cylinder volume and P is the cylinder pressure. At the same time, analyzes of other combustion characteristics such as ignition delay (ID), start of ignition (SoI), start of combustion (SoC), and combustion duration were also performed.

2.4.Test Fuels

The ethanol used in the experiments has been produced from sugar beet, and was obtained from a local sugar factory. The fossil based methanol was supplied by a chemical materials manufacturer. Test fuels were coded as E10 (90% gasoline + 10% ethanol) and M10 (90% gasoline + 10% methanol) which are also used in worldwide. Some important fuel properties of test fuels have been given in Table 3.

Table 3. Some important properties of test fuels

Properties	Gasoline	E10	M10
Density, g/cm^3 (at 20^{o}C)	0.729	0.737	0.743
Viscosity, mm^2/s (at 40^{o}C)	0.565	0.618	0.524
LHV, MJ/kg	42.58	40.9	40.32
Oxygen Content, %	-	3.67	4.88
Purity, %	-	99.95	99.98

2.5.Experimental Procedure

The experiments were carried out for twelve different engine speeds with 100 rpm of ranges between 2100-3200 rpm at full throttle opening. Before starting to the measurements, the engine was heated up to optimal working temperature (approximately 80-85^{o}C). While experiments were performed, both temperatures of air and fuel were nearly constant (± 2^{o}C). All data (torque, fuel consumption, exhaust gas temperature, cylinder pressure and emission parameters) were measured and saved simultaneously.

3. Results and Discussion

The experiment results were investigated under three headings as combustion analyzes, engine performance parameters and exhaust emission characteristics. All results were presented as graphical, and compared. The combustion analyzes performed for 2500 rpm which was speed obtained of maximum engine torque for each test fuel.

3.1.Combustion Analyzes

The variation of the cylinder gas pressure with respect to the crankshaft angle at the engine speed of 1500 rpm is shown in Figure 2. The max cylinder gas pressure has been obtained with the use of gasoline. Later, methanol and ethanol have highest cylinder pressure values respectively. Numerical data of cylinder pressure values are presented in Table 4. It is showing that alcohols shortened combustion duration due to their oxygen content. Because, oxygen causes burning to end before the pressure rises. But, it is observed that M10 has higher peak pressure according to E10 due to methanol has higher oxygen content than ethanol. Similar results were also reported by Eyidogan et al. [26], Balki and Sayin [27], and Zhuang et al. [28].

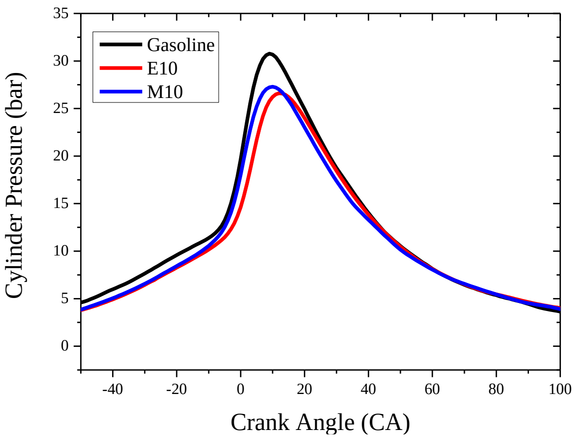

Fig. 2. Cylinder pressure values of test fuels at 2500 rpm

HRR changes of test fuels is given in Figure 3. Although the max HRR values of both E10 and M10 were lower than that of gasoline, HRRs increased after especially crank angles obtained of peak pressures. The max HRR value of M10 was obtained higher compared E10 due to methanol has higher oxygen content according to ethanol in as seen Table 3. Table 4 shown HRR behaviors of fuels.These results is also seen in previous similar studies [29-32].

While Figure 4 show detailed combustion characteristics, total combustion durations (TCD) of test fuels is presented in Figure 5. The ignition time (IT) is the moment occurring of spark in plug, and it happened at 25 CA before top dead center for all fuel. The start of combustion is the moment start to burning of fuel, and the period between IT and SoC is also called as ignition delay (ID). CA5-CA90 terms is denote crank angle location of 10% accumulated HRR, so angular change at burning amount of fuel as mass. For example, if CA50 is -10 CA, it means that 50% of fuel burned at -10 CA. Although CA90 is accepted as the end of combustion (EoC) in many studies [33-38], some researchers have presented actual values of EoC[39-41]. The detailed values for investigated all combustion characteristics is given in Table 4.

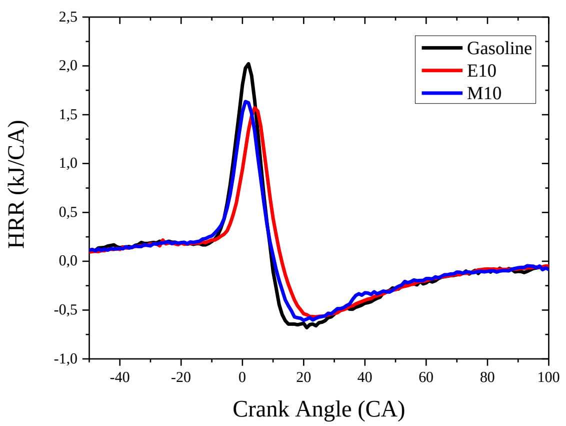

Fig. 3.HRR values of test fuels at 2500 rpm

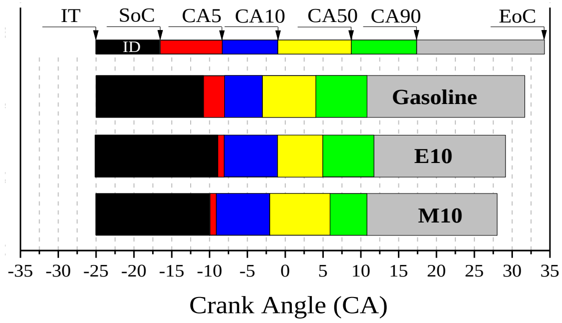

Fig. 4. Combustion characteristics of test fuels

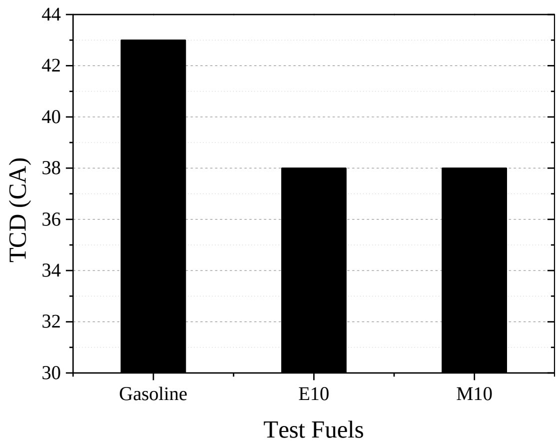

Fig. 5. Total combustion duration of test fuels

The ID values of both E10 and M10 were obtained higher according to gasoline due to less volatility properties of ethanol and methanol. Because, the less volatility is caused late SoC [42]. On the other hand, M10 has lower ID value compared E10, because volatility of methanol is more according to ethanol [43-44]. But, E10 and M10 have burned faster compared to gasoline after combustion started. Although E10 and M10 have equal TCD values, high oxygen amount in methanol caused faster burn of M10. Besides, high octane number of methanol causes faster flame speed. Thus, the burn rate also increases. There is a direct correlation between the flame speed and the octane number, as the flame speed will allow the fuel to run out without knocking [45].Laminar flame speed of the methanol and ethanol were reported by Li et al [46].CA50 duration of E10 is shorter due to the more volatility value of ethanol according to methanol. But, higher oxygen amount in methanol caused earlier CA90 value for M10, and thus EoC of M10 fuel shortened according to both gasoline and E10 fuel.

Table 4. Detailed combustion characteristic values

Characteristics	Gasoline	E10	M10
Max pressure, bar	30.77	26.61	27.29
CA of max pressure	9	12	10
Max HRR, kJ/CA	2.022	1.571	1.635
CA of max HRR	2	4	1
CA of Soc	-11	-9	-10
ID, CA	-14	-16	-15
CA of CA5	-8	-8	-9
CA of CA10	-3	-1	-2
CA of CA50	4	5	4
CA of CA90	11	12	11
CA of EoC	32	29	28
TCD, CA	43	38	38

3.2.Engine Performance Parameters

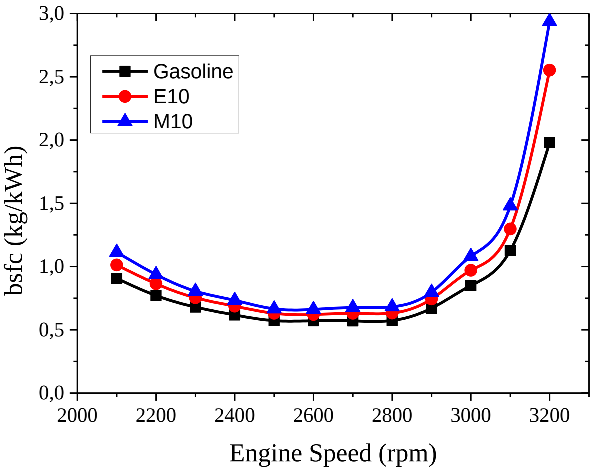

Fig. 6. The bsfc values of test fuels

The bsfc is fuel amount consumed for obtaining of unit power. It is one of the most important performance parameters that can be used for performance comparisons of different fuels. The bsfc changes of test fuels depend engine speed is given in Figure 6. Ethanol and methanol addition have increased bsfc values by average 15.22% and 27.1% for E10 and M10 fuels, respectively according to gasoline. Besides, bsfc values of M10 fuel are higher by average 10.3% than E10 fuel. The most important reason of drop in bsfc values with alcohol addition is lower calorific value of ethanol and methanol than that of gasoline. Doğan et al. [47],Phuangwongtrakul et al. [48] and Thakur et al. [49], in their studies, have also presented increasing of bsfc values due to low calorific value.

Figure 7 show bte trends of test fuels. The bte is an indicator of transformed ratio to useful work of thermal energy of fuel. Likewise, bte also depends calorific value of fuel, primarily. According to experiment results, while E10 has lower bte values by average 6.7% than gasoline, the bte values of M10 have decreased by average 12.39%. Besides, methanol decreased bte values by average 6.12% compared to E10 due to its lower calorific value according to ethanol. These results agree with the studies conducted by Li et al. [50], Mourad and Mahmoud [51], and Lemaire et al. [37].

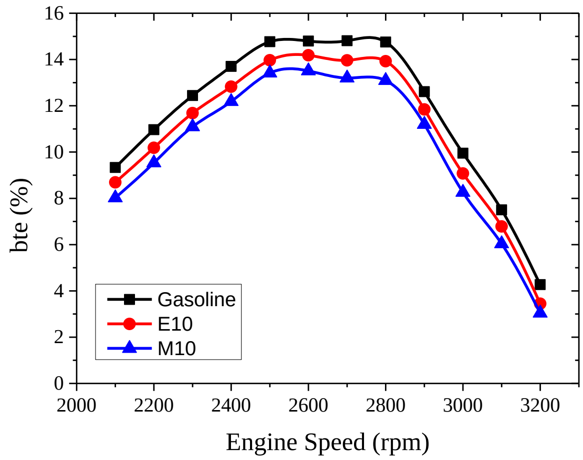

Fig. 7. The bte values of test fuels

3.3.Exhaust Emissions

Exhaust gas temperature helps to execution of ideas about the combustion quality and in the interpretation of the formation of exhaust emissions. The oxygen content of alcohol improves combustion, thus temperature in end of burn is increase. Both oxygen and high temperature in cylinder causes increment of exhaust gas temperatures. But, a slightly increase has happened due to ratio of ethanol and methanol in gasoline are low. Max exhaust gas temperature values obtained for gasoline, E10 and M10 are 478.5ºC, 482.9ºC and 480.1ºC, respectively. Max temperature values were obtained at 2600 rpm engine speed for all fuels as seen in Figure 8.

The oxygen amount in exhaust gases depends oxygen content of fuels. Besides, air amount received in cylinder at intake stroke also effects oxygen emission. Furthermore, alcohol addition into gasoline also causes decrease in ratio of stoichiometric air-fuel. The highest oxygen emission was obtained from M10 fuel due to methanol has higher oxygen content. The increment in oxygen emission according oxygen amount in fuel is also observed in Figure 9. While this increase is by average 5.44% with E10 fuel, it is by average 21.57% with M10 fuel compared gasoline. Besides, M10 fuel has higher oxygen emission by average 15.3% according to E10 fuel.

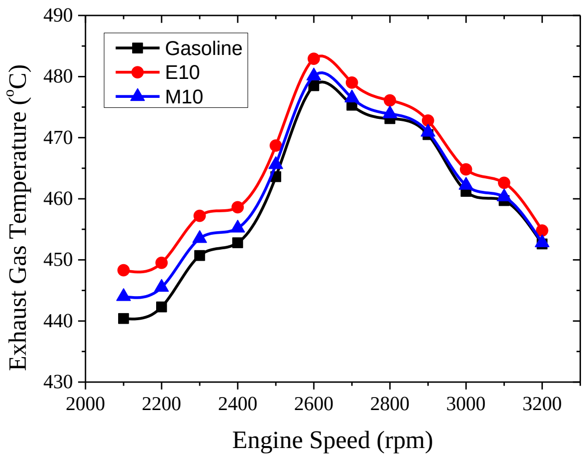

Fig. 8. Exhaust gas temperature values of test fuels

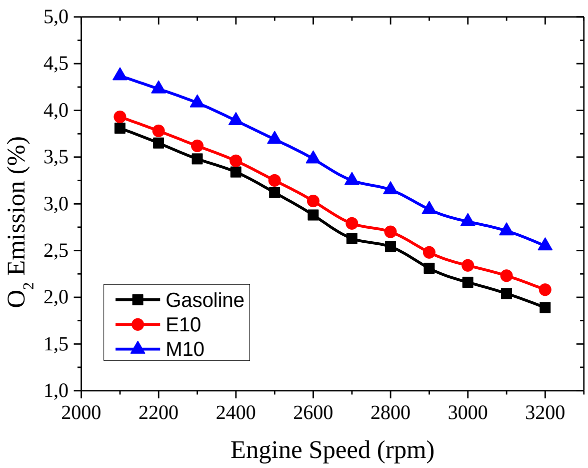

Fig. 9. O_2 emission values of test fuels

CO_2 is a gas released normally by the burning of hydrocarbon fuels. The amount of CO_2 in the exhaust gases increases as the C atoms react with a sufficient amount of O atoms during combustion. So, CO_2 emission increases due to oxygen amount in fuel, and Figure 10 is an indicator of this increment. E10 fuel has higher CO_2 emission values by average 10.7% and 6.48% respectively according to gasoline and M10 fuel. Although methanol contains higher O atom, it has lower CO_2 emission than E10 fuel due to it has lower C atom compared ethanol. Balki and Sayın [27] and Chen et al. [35] have also observed similar results due to same reasons. One the other hand, some although researchers have claimed that they should cause lower CO_2 emission thanks to both ethanol and methanol have lower C atoms, they revealed that C atoms in cylinder at unit stroke will be too much since the amount of fuel taken into the cylinder to obtain the same engine power will be higher for alcohols [8, 52].

CO emission occurs due to insufficiency of oxygen during combustion. The oxygen in ethanol and methanol have decreased CO emission by average 25% and 44.9% respectively according to gasoline. Additionally, the lowest CO emission values were obtained with M10 fuel thanks to methanol has high oxygen content, and it is lower by average 26.6% than that of E10 fuel as seen in Figure 11. Elfasakhany [53] and Doğan et al [47] have also presented similar results. Besides, Doğan et al. have denoted that ethanol ensures a cleaner combustion thanks to its better evaporation compare to gasoline, thus decrease of CO emissions [47].

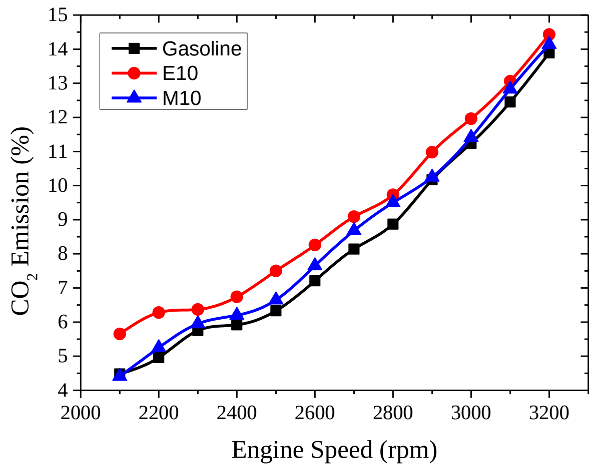

Fig. 10. CO_2 emission values of test fuels

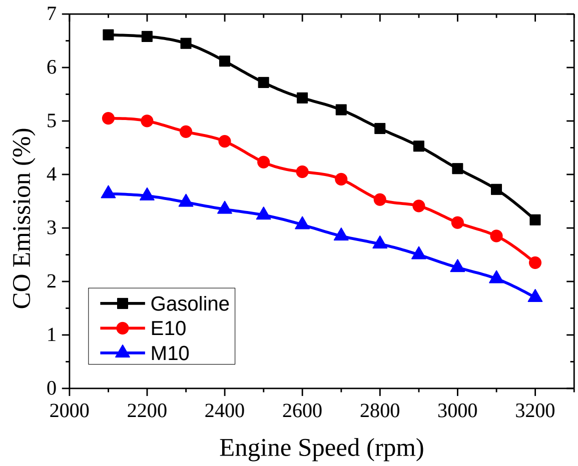

Fig. 11. CO emission values of test fuels

Unburned hydrocarbon emission changes of test fuels at different engine speeds are shown in Figure 12. Average reduction amounts of HC emissions in the use of E10 and M10 fuels compared to gasoline are 18% and 21.9%, respectively. The oxygen in alcohols has provided cleaner combustion, and thus, HC emissions have decreased. Besides, ethanol and methanol have improved combustion efficiency, and this can also prove with results of exhaust gas temperature. Another reason of decrease in HC emissions is also it. Turner et al. [54] and Melo et al. [55] have also reported to obtaining of similar results.

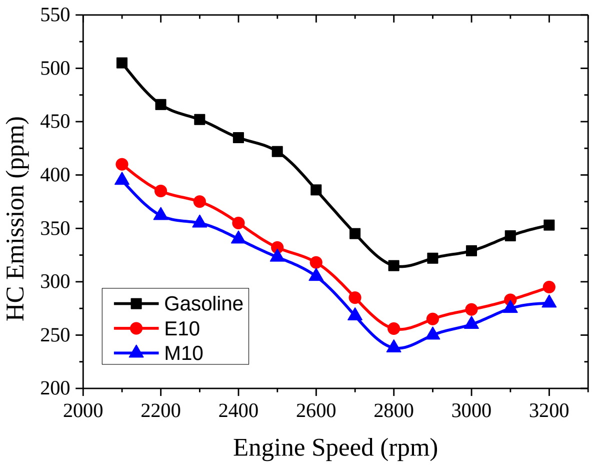

Fig. 12. HC emission values of test fuels

Alcohols have caused to increment of NOx emissions due to both high exhaust gas temperature and oxygen content as seen in Figure 13. The highest NOx emission was achieved with E10 having the highest exhaust gas temperature values rather than the highest oxygen-containing methanol. While ethanol addition increased NOx emissions by average 16.8% compared to gasoline, NOx emission values obtained with methanol were lower by average 9.16% according to E10 fuel. In studies of Najafi et al. [56] Keskin and Gürü, [57]; Schifteret al. [58] have also revealed similar trends.

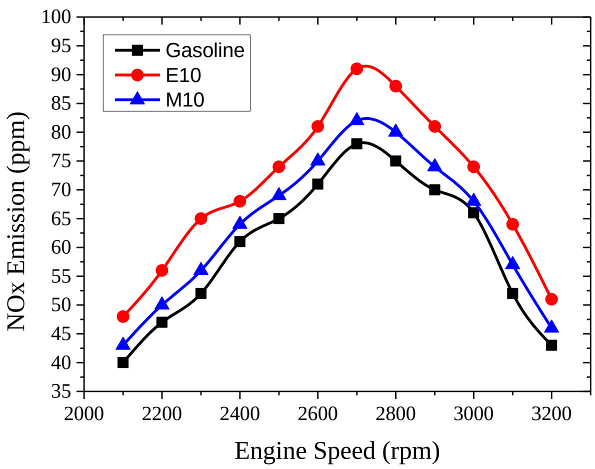

Fig. 13. NOx emission values of test fuels

4. Conclusions

The aim of this study was to also demonstrate the usability of methanol such as ethanol for SI engines. Comparison of experimental results with the ethanol addition of the addition of 10% methanol into the gasoline is summarized below.

- M10 fuel shown similar combustion characteristics with E10 fuel. The higher oxygen in content of methanol has caused a little faster burning of M10 fuel compared to E10 fuel.
- Although both alcohol effected engine performance negatively, methanol addition has increased bsfc by 10.3%, has decreased bte by 6.12% according to E10 fuel.
- Alcohols caused cleaner combustion, resulting in improvement of all emissions except NOx emissions. While NOx emission increased with use of E10 and M10 fuels according to gasoline due to their higher exhaust gas temperature values, NOx emission of M10 fuel decreased by 9.17% compared to E10 fuel. The M10 fuel has lower CO and HC emissions by 26.6% and 4.75% respectively than E10 fuel. The ethanol which has higher C atoms amount according to methanol, increased CO_2 emission by 6.48% and 10.7% respectively compared to both M10 fuel and gasoline.

Consequently, as an alternative to ethanol, the use of methanol by adding 10% into gasoline is particularly suitable for emissions values. In addition, since it has a high octane number, it can be achieved to increase the compression ratio, thus achieving higher performance values.

Acknowledgment

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Nomenclature

SI	:spark ignition
bsfc	:brake specific fuel consumption
bte	:brake thermal efficiency
LHV	:lover heating value
HRR	: heat release rate
CA	: crank angle
ID	: ignition delay
SoI	: start of ignition
SoC	: start of combustion
E10	: 90% gasoline + 10% ethanol
M10	: 90% gasoline + 10% methanol
TCD	: total combustion duration
IT	: ignition time
EoC	: end of combustion

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