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Effects of Methanol Addition to Gasoline on the Performance and Fuel Cost of a Spark Ignition Engine

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This study is concerned with investigating experimentally the effects of methanol blending to base gasoline on the performance and fuel cost of a spark ignition (SI) engine. The fuel blends were prepared by blending 5, 10, 15, and 20 vol % of methanol with a specified amount of base gasoline. These fuel blends were designated as M5, M10, M15, and M20, respectively. Base, leaded, and unleaded gasolines were also used in the study. The experiments were conducted under various engine speeds, spark timings (STs), and compression ratios (CRs). The engine was operated under wide-open-throttle (WOT) conditions. The result of the study showed that the M5 blend yields the best engine performance in terms of the brake mean effective pressure (bmep), while the M20 blend suggests the best performance in terms of brake thermal efficiency (bte). The economical analysis performed in the study is based on both the current blending fuel prices in Turkey and brake-specific fuel consumption (bsfc) of the engine while using base gasoline and gasoline−methanol blends. It was obtained that, in contrast to the improvement of engine performance, methanol blending caused an increase in the consumed fuel cost because of the expensive methanol price in Turkey. The increments in the cost of the fuel blends compared to base gasoline were determined as 18.86, 36.95, 54.20, and 73.01% for M5, M10, M15, and M20, respectively. Uncertainty analysis was also performed in this study, and it was found that the uncertainties in the measurement devices do not have noticeable influences on the variations of engine characteristics.

1. Introduction

Worldwide depletion of petroleum reserves, continuing increases in oil prices, growing environmental concerns, and worries about energy security and future oil supplies have intensified the studies on the nonpetroleum-based environmentally friendly alternative fuels.[1–3] The favorable alternative fuels should be abundant, cheap to compete with conventional fuels and, either be replaced with or be added to the present conventional fuels to decrease the dependency on petroleum-based fuels. Methanol can be considered as one of the alternative fuels in this respect. It can be produced from coal, natural gas, biomass, and even combustible trash and municipal wastes.[3,4] Producing of methanol from coal is important, because coal is the most abundant energy resource in the world that could supply our future fuel needs in the long term.[3]

As a fuel for SI engines, methanol has some advantages over gasoline, such as better antiknock characteristics and the reduction of carbon monoxide (CO) and unburned hydrocarbon (UHC) emissions.[3–10] The oxygen presence in methanol also provides a soot-free combustion with a low particulate level.[11]

Table 1. Properties of the Fuels Used in This Study

property	base	leaded	unleaded	methanol
chemical formula		$C_{6-8.3}H_{13.1-18}$[a]		CH_3OH
molecular mass (kg/kmol)		86−115[a]		32.04
oxygen percent (wt %)		50		
density (kg/m^3)	710−740[a]	725−760[a]	725−780[a]	793
boiling temperature (°C)		26.7−225[a]		64.9
Reid vapor pressure (kPa)		41−103[b]		34[b]
latent heat of vaporization (kJ/kg)		300−350[a]		1160
lower heating value (kJ/kg)	43 075[c]	42 560[c]	41 572[c]	20 000
stoichiometric air−fuel ratio (AFR$_s$)		14.5[d]		6.47[d]
research octane number (RON)	91[a]	95[a]	95[a]	107
motor octane number (MON)	80[a]	84[a]	85[a]	92

[a] From the catalogue of Turkish Petroleum Office Company. [b] From ref 5. [c] From tests that were performed in a laboratory of the Department of Chemistry at KTU. [d] Mass basis.

A higher flammability limit and flame speed and lower carbon/hydrogen ratio of methanol can be considered as some other advantages over gasoline.[5,12] Methanol burns more efficiently under lean conditions than gasoline.[5] Higher latent heat of evaporation cools the air entering the engine and increases the volumetric efficiency and power output.[5,6] Recently, these excellent combustion properties of methanol have made it the strongest choice of the automotive industry.[13–15]

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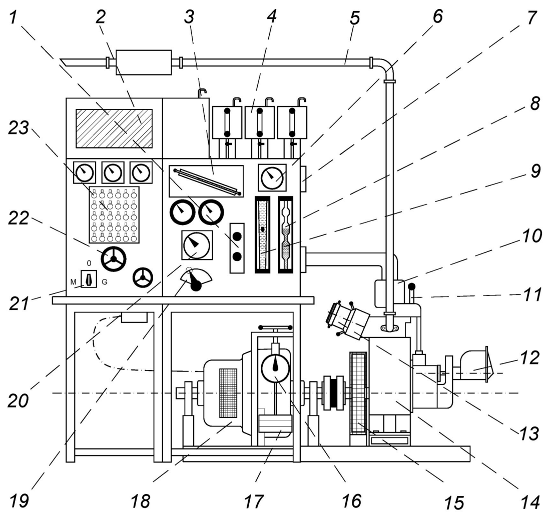

1. Start/stop
2. Electric resistances
3. Inclined manometer
4. Fuel tanks
5. Exhaust pipe
6. Tachometer
7. Orifice meter & surge tank
8. Fuel flow meter
9. Rotameter
10. Carburetor
11. Decompression lever
12. Ignition module
13. Compression ratio changing unit
14. Test engine
15. Flywheel
16. Weighing device
17. Balancing weights
18. Electrical motor/dynamometer
19. Throttle controller
20. Exhaust gas thermometer
21. Motor/generator selector
22. Loading rheostat
23. Loading keys

Figure 1. Schematic layout of the experimental setup.

Table 2. Engine Specifications

cycle	four stroke
cooling system	water cooled
number of cylinders	1
bore × stroke (mm)	90 × 120
displacement volume (cm^3)	763.4
compression ratio	variable (7.5−24.5)

Besides the mentioned advantages above, methanol also has some limitations as a motor fuel, as well. It is corrosive, highly toxic, colorless, odorless, and tasteless.[1,5,12] In addition, its energy density is lower than that of gasoline because of the high atomic weight of the oxygen that it contains.[12] On the mass basis, gasoline provides over twice of a lower heating value of methanol. Neat methanol has a cold-starting problem because of its high latent heat of vaporization,[5] and gives higher NO emissions at very lean operating conditions.[3] Phase separation, high volatility, and an increase in aldehyde emissions in exhaust can be considered as additional potential limitations.[1] Methanol has a marked effect on the volatility of methanol−gasoline blends. The introduction of small quantities of methanol into gasoline results in large increases in Reid vapor pressure, which tends to give the engine high-temperature driveability problems, such as vapor lock.[1,5] However, using suitable solutions can eliminate most of the limitations mentioned above. For example, blending the methanol and gasoline at the service station pump would be one way of preventing phase separation in the fuel distribution system.[1] To reduce the corrosion problem, it should be avoided to use copper, brass, aluminum, or rubber materials in fuel-delivery system. It is advised to use fluorocarbon rubber as a replacement for rubber,[6] for example.

Having good combustion properties and mostly eliminative problems make the methanol a strong alternative fuel for SI engine applications. Therefore, there are numerous studies in the literature on using methanol in SI engines either pure or as a blending component. However, there has been a scarcity in the existing literature on the economical analysis based on both "fuel prices" in the market and "fuel consumption" of the engine. In some countries, such as China, methanol can be the cheapest alternative liquid fuel per calorific unit[13] and blending methanol to gasoline does not make any negative effect on the consumed fuel price. However, in some other countries, such as Turkey, the price of methanol is almost 5 times as expensive as gasoline per liter. Thus, even though the fuel consumption of the engine decreases, the cost of the fuel blend can increase because of the high methanol price in the blend. Therefore, an economical analysis based on blending fuel prices and engine fuel consumption should be carried out in the studies about using fuel blends in engines. The aim of this study is to perform an economical analysis in addition to the performance analysis of a SI engine using gasoline−methanol blends. The uncertainty analysis was also performed in the study, which has been mostly disregarded in the experimental studies on internal combustion engines.

2. Experimental Section

2.1. Properties of the Fuels. In this study, Merck pure-grade methanol having a purity of 99.9% was used. Blended fuels were prepared by adding 5, 10, 15, and 20 vol % of methanol to a certain amount of base gasoline. The blends were prepared just before starting the experiments to obtain a homogeneous mixture and prevent phase separation. Properties of methanol and base, leaded, and unleaded gasolines are given in Table 1.

2.2. Experimental Setup and Test Procedure. The test bed consisted of a test engine, the measurement instruments, and a control panel. A schematic layout of the test bed is shown in Figure 1. The engine used in the experiments is a single cylinder, variable compression, four-stroke engine, which can operate as a SI or compression ignition engine by replacing the engine head. The major specifications of the engine were given in Table 2. The test engine is coupled to an electrical dynamometer, which is used to load the engine and measure the engine output torque. A calibrated burette and stopwatch were used to measure the engine fuel consumption. The mass flow rate of air was measured by means of an orifice and an inclined manometer. The ambient pressure and temperature of the test room were measured using a barometer and thermometer, respectively.

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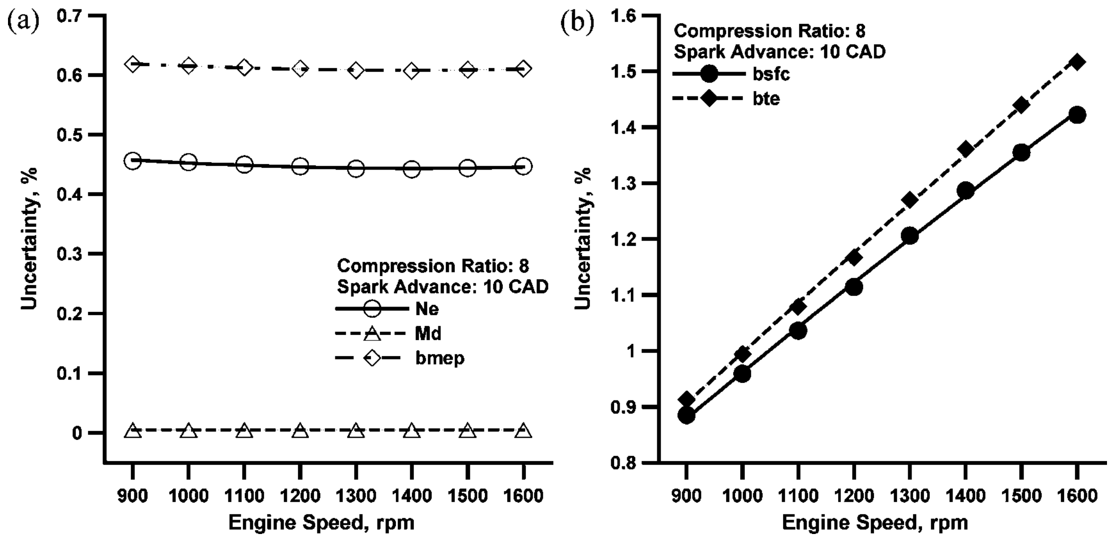

Figure 2. Variations of uncertainties with engine speed.

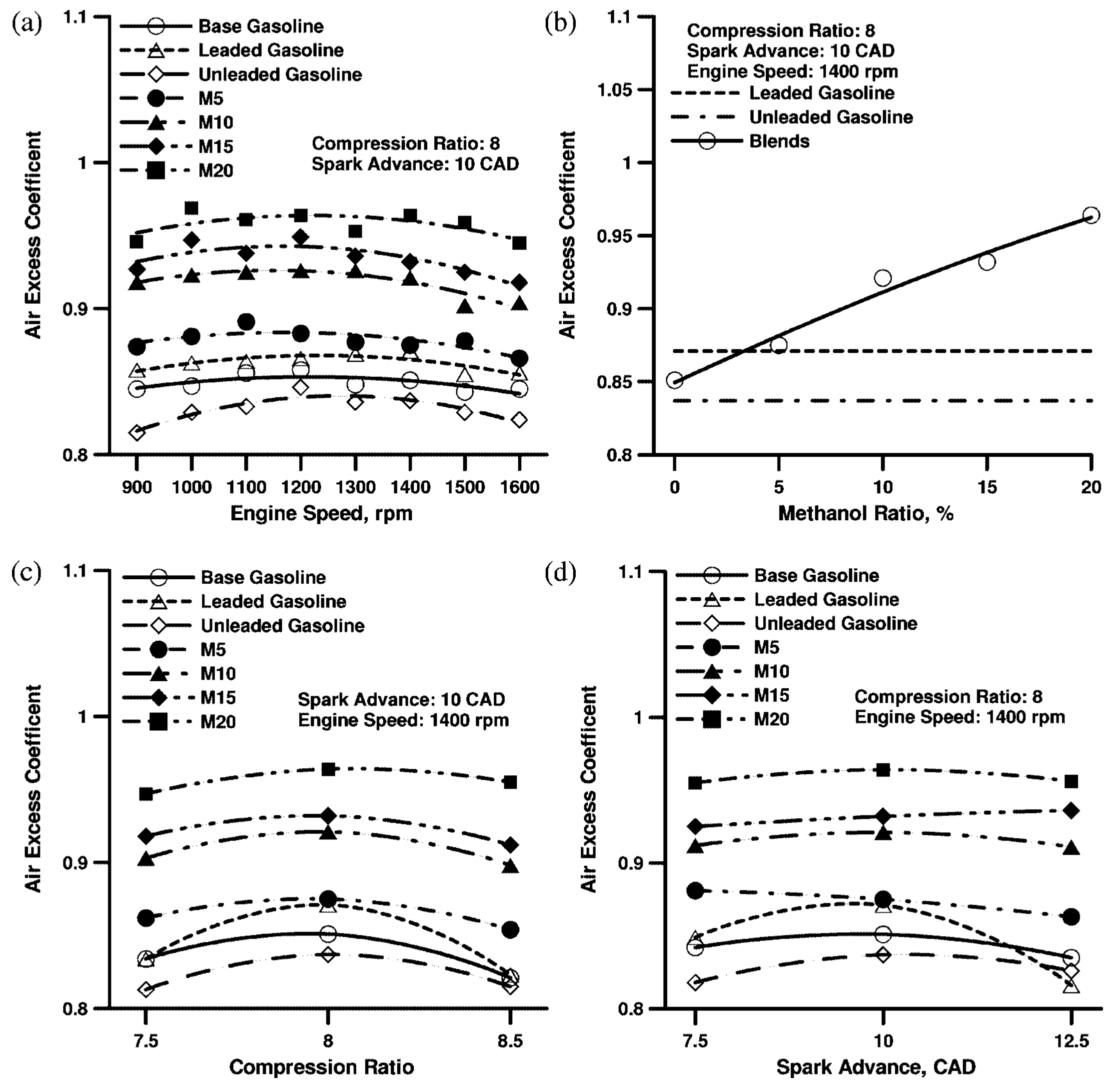

Figure 3. Variations of AEC at various operating conditions.

The experiments have been performed for the CRs of 7.5, 8, and 8.5 and STs of 7.5, 10, and 12.5° before top dead center (BTDC). The engine was operated at WOT, and engine speed was varied from 900 to 1600 rpm via load adjustment. The carburetor setting, which was initially adjusted for base gasoline, was not varied throughout the experiments. The experimental data were recorded after the engine had reached the steady operation conditions. The brake torque, the flow rate of fuel, and the mass flow rate of air were measured during the experiments, and these measured parameters have been used to calculate the engine performance parameters. Additionally, the wet- and dry-bulb temperatures of the ambient air and the atmospheric pressure were also measured during each test. Finally, the engine performance parameters were corrected to the standard atmospheric conditions

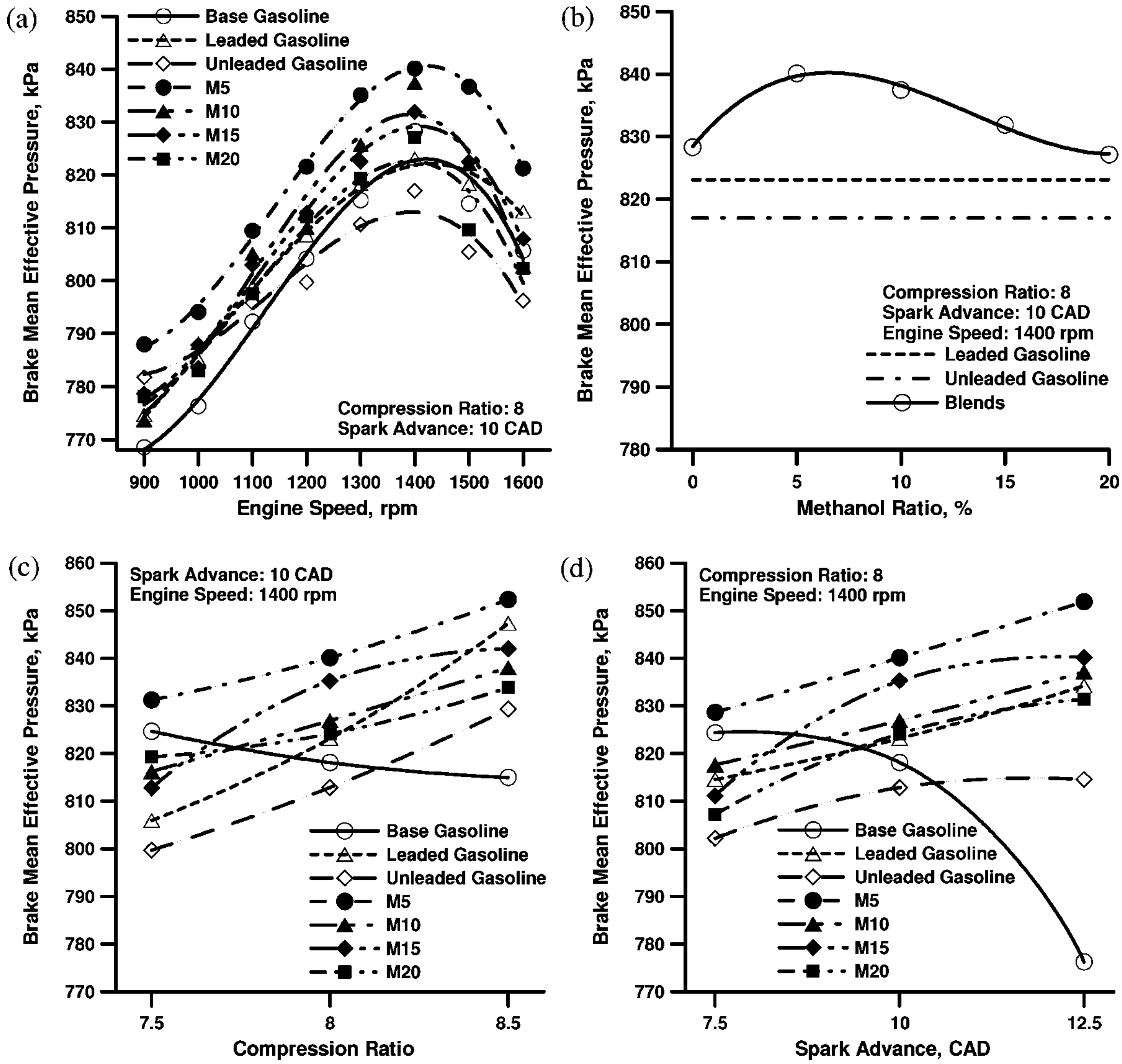

Figure 4. Variations of bmep at various operating conditions.

by taking into account the measured bulb temperatures, atmospheric pressure, and humidity of the ambient air. The experimental analysis are presented in the next section, and further details can be found in refs 16–18.

3. Analysis

3.1. Performance Parameters. The brake power of the engine was calculated using the following formula:

$$N_{e,1} = M_d \omega \tag{1}$$

where, $\omega = \pi n/30$ is the angular speed of the crankshaft. The calculated brake power was converted to the standard atmospheric conditions by taking into account the humidity X_{hum} of air and the atmospheric conditions P_0 and T_0 as

$$N_e = N_{e,1} \frac{0.1013}{P_0} \sqrt{\frac{T_0}{293}} X_{hum} \tag{2}$$

The humidity correction factor X_{hum} in eq 2 was determined from the psychometric chart considering the dry and wet thermometer bulb temperatures.

The stoichiometric air–fuel ratio ($AFR_{s,blend}$) and lower heating value (LHV_{blend}) of the blends were determined as

$$AFR_{s,blend} = \frac{\sum x_i \rho_i AFR_{s,i}}{\sum x_i \rho_i} \tag{3}$$

$$LHV_{blend} = \frac{\sum x_i \rho_i LHV_i}{\sum x_i \rho_i} \tag{4}$$

where the subscript i refers to the gasoline or methanol and x_i and ρ_i refer to the volume ratio and density, respectively, of the gasoline or methanol in the blend.

3.2. Economical Analysis. As mentioned in the Introduction, there are many studies in the literature about the effects of blends on engine performance, but there is a scarcity about economical analysis based on both each fuel price and fuel consumption of the engine. Because the fuel prices are different in the market, even though the blends give lower fuel consumption than base fuel, the total cost may increase according to the price of the blending agent. For this reason, an economical analysis should be carried out based on both each fuel price and fuel consump-

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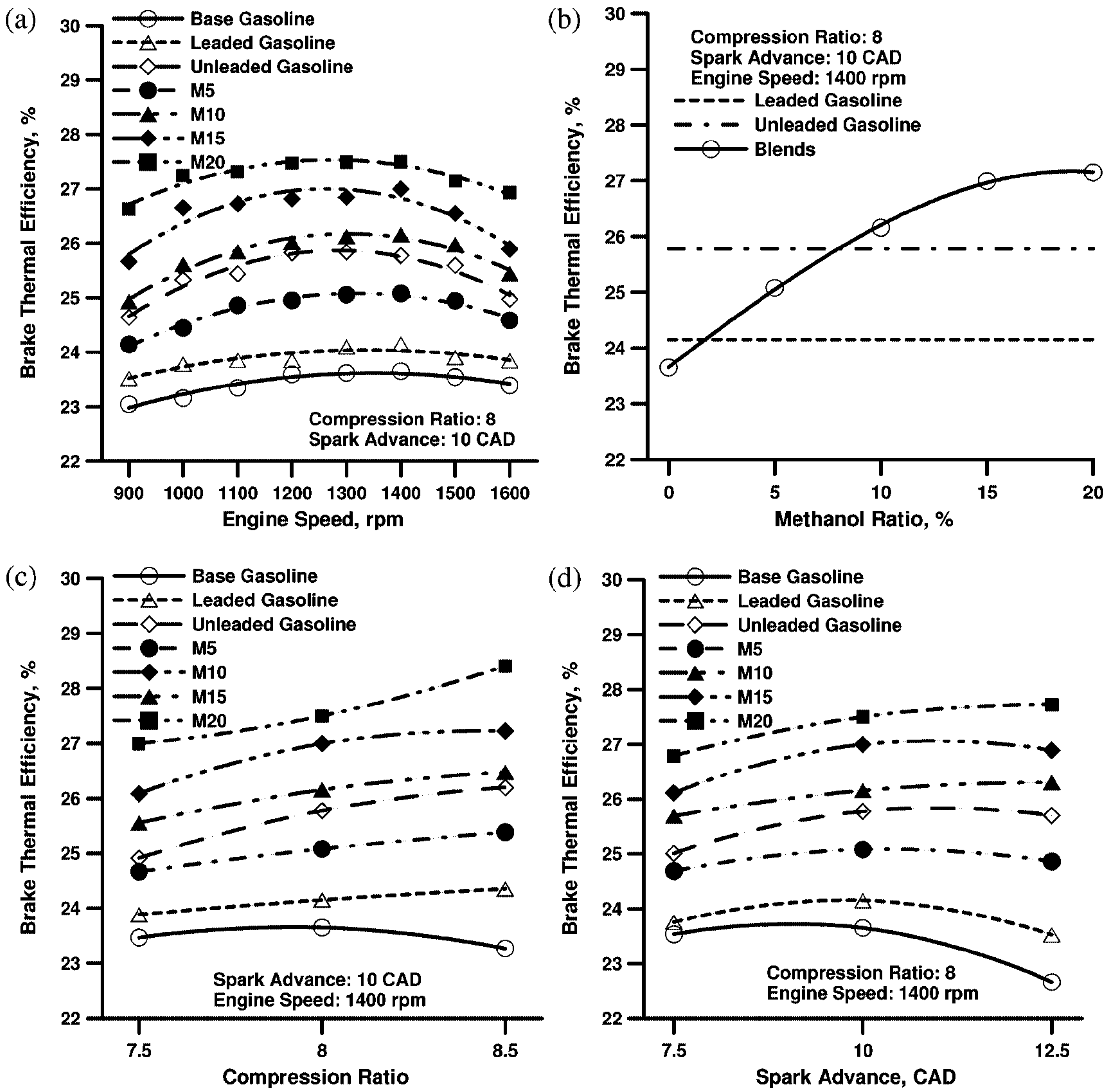

Figure 5. Variations of bte at various operating conditions.

tion of the engine. The relationship developed originally by Durgun[19] and given by Şahin and Durgun[20] is very suitable in this respect and was used in this study

$$\frac{\Delta F}{F_{\text{base}}}\times 100=\left\{\frac{\text{bsfc}_{\text{blend}}}{\text{bsfc}_{\text{base}}}\left(\frac{\sum x_i r_i}{\sum x_i s_i}\right)-1\right\}\times 100 \qquad (5)$$

In eq 5, x_i refers to the ratio of blending components. r_i and s_i are the ratios of price per liter and density of the blending component to the base fuel, respectively, as follow:

$$r_i=\frac{f_i[\$/\text{L}]}{f_{\text{base}}[\$/\text{L}]} \quad \text{and} \quad s_i=\frac{\rho_i[\text{kg/m}^3]}{\rho_{\text{base}}[\text{kg/m}^3]} \qquad (6)$$

Therefore, r_i and s_i are dimensionless quantities and, for $i = 1$, $f_1 = f_{\text{base}}$ and $r_1 = 1$; for $i = 2$, $f_2 = f_{\text{methanol}}$ and $r_2 = f_{\text{methanol}}/f_{\text{base}}$. Similarly, $s_1 = 1$ and $s_2 = \rho_{\text{methanol}}/\rho_{\text{base}}$.

For only blending of two components, i.e., gasoline as a base fuel and methanol as a blending agent, for example, eq 5 becomes

$$\frac{\Delta F}{F_{\text{gasoline}}}\times 100= \left\{\frac{\text{bsfc}_{\text{blend}}}{\text{bsfc}_{\text{gasoline}}}\left(\frac{x_{\text{gasoline}}+x_{\text{methanol}}(f_{\text{methanol}}/f_{\text{gasoline}})}{x_{\text{gasoline}}+x_{\text{methanol}}(\rho_{\text{methanol}}/\rho_{\text{gasoline}})}\right)-1\right\}\times 100 \qquad (7)$$

Considering the current prices of base gasoline and Merck pure-grade methanol in Turkey as \$2.3/L and \$11.5/L, the increments in the cost of blends compared to base gasoline have been determined as 18.86, 36.95, 54.20, and 73.01% for M5, M10, M15, and M20, respectively. These results show that methanol blending to gasoline is economically not feasible in Turkey with the current high methanol price.

3.3. Uncertainty Analysis. The results of the experiments calculated from several measured physical quantities generally have certain uncertainties. Therefore, the results have uncertainties because of the uncertainties in the primary measurements. The method used for estimating the uncertainties in this study was developed originally by Kline and McClintock and given in refs 21 and 22. According to this method, if the result R is a function of the independent variables $x_1, x_2,..., x_n$, it can be expressed as

$$R=R(x_1,x_2,...,x_n) \qquad (8)$$

Then, the uncertainty in the result U_R can be calculated using the following root-sum-of-the-squares rule

$$U_R=\sqrt{U_{R,1}^2+U_{R,2}^2+...+U_{R,n}^2}=\sqrt{\sum_{i=1}^{n}U_{R,i}^2} \qquad (9)$$

The $U_{R,i}$ values in the above equation, corresponding to the uncertainties of each measured quantity x_i, are determined as follows:

$$U_{R,i} = \left|\frac{\partial R}{\partial x_i}\right| U_i \quad (1 \le i \le n) \tag{10}$$

The above approximation is also called as partial uncertainty in the result because of the dependence on a measured quantity x_i and its uncertainty U_i.

The uncertainty in the torque, for example, comes from the measured force and the length of the moment arm, which have uncertainties of ±0.5 N and ±1 mm, respectively. Considering these uncertainties, the calculated uncertainty in the brake torque becomes 0.005% for the speed range of the test engine. The other uncertainties for calculated engine characteristics are in the range of 0.44−0.46% for effective power, 0.60−0.62% for bmep, 0.91−1.52% for bte, and 0.89−1.42% for brake-specific fuel consumption. Variations of these uncertainties with respect to engine speed were also given in Figure 2. It should be noted that the calculated uncertainties in the main engine characteristics do not have noticeable influences on the variation of the engine characteristics.

4. Results and Discussion

Air Excess Coefficient (AEC). Figure 3 shows the variations of the AEC with various operating parameters. Figure 3a shows the effect of engine speed on AEC for a CR of 8 and a ST of 10° BTDC. As seen from the figure, the AEC increases with an increasing methanol ratio for all engine speeds. The highest AEC was obtained with the M20 blend, while the lowest one was obtained with the unleaded gasoline. The leaded gasoline gave a higher AEC than the base gasoline. The dependence of AEC on the methanol percentage is more clearly shown in Figure 3b for the same operating conditions as in Figure 3a and at an engine speed of 1400 rpm. The increase in AEC with an increasing methanol percentage can be attributed to both "cooling" and "leaning" effects of methanol. As seen in Table 1, the latent heat of vaporization of methanol is considerably higher than that of gasoline. The addition of methanol to base gasoline results in an increase in the latent heat for the blends compared to that for base gasoline, which results in a cooler and, hence, denser charge induced. Additionally, methanol has a lower AFR_s than gasoline because of the oxygen content in its basic form. Therefore, the addition of methanol to base gasoline results in a reduction in AFR_s for the blends compared to that for base gasoline. This means that the actual air−fuel ratio for the blend becomes higher relative to AFR_s, which gives a higher AEC. Variations of AEC as a function of CR and ST are also given in parts c and d of Figure 3, respectively.

Brake Mean Effective Pressure. Results of bmep at various operating conditions were given in Figure 4. In this study, the bmep is preferred as an engine-output parameter because it enables one to compare the results without considering the engine dimensions. Figure 4a shows the variations of bmep with the engine speed for a CR of 8 and a ST of 10° BTDC. The blends gave higher bmep values than base, leaded, and unleaded gasolines for almost all engine speeds. The best performer is the M5 blend, especially at engine speeds higher than 1300 rpm. The effect of the methanol ratio on bmep was given in Figure 4b, for the same operating conditions as in Figure 4a and at an engine speed of 1400 rpm. As can be seen from the figure, bmep increases with an increasing methanol ratio up to 5% and then it decreases. Thus, the best performance was acquired with the M5 blend. This variation in bmep with the methanol ratio can be attributed to the lower calorific value of the methanol than that of gasoline, besides cooling and leaning effects. The oxygen presence in the methanol also assists to homogenize the fuel−air mixture in the cylinder and therefore to improve combustion efficiency, which makes a contribution to the increase in bmep by 5% with the methanol ratio. A further addition of methanol beyond 5% causes the decrease in energy content of the blend and therefore results in a decrease in bmep of the domination of the lower calorific value of methanol over the gain of improved combustion efficiency. The effects of the CR on bmep were given in Figure 4c. As expected, increases in CR result in the increases in bmep for the blends and gasolines except for the base gasoline. The lower octane rating of base gasoline compared to other gasolines and blends results in knocking combustion as CR increases. It is known that knocking combustion in a SI engine causes a very high rate of energy release and excessive temperatures and pressures inside the cylinder, therefore adversely affecting the performance and efficiency of the engine. A variation of bmep with respect to ST was given in Figure 4d. As shown in this figure, base gasoline gives the best performance for the lower spark advances in contrast to the leaded and unleaded gasolines. On the other hand, the blended fuels gave the best performances for the higher values of STs for the selected spark advance range. The noticeable result that can be concluded from Figure 4 is that the M5 blend gives the best bmep values for the operating conditions manifest in the figure. The increments in bmep obtained with the M5 blend are about 1.5, 2.1, and 2.9% in comparison to those of the base, leaded, and unleaded gasolines for the mentioned operating conditions, respectively.

Brake Thermal Efficiency. Variations of the bte with engine speed, methanol percentage, CR, and ST were given in parts a−d of Figure 5, respectively. As shown in Figure 5a, bte values increase with an increasing methanol ratio. The M20 is the best performer among the blends and gasolines for the tested engine speeds. The lowest bte was obtained with base gasoline. Unleaded gasoline gave better efficiency than the other gasolines and the M5 blend. The dependency of the bte/methanol ratio was more clearly shown in Figure 5b for a CR of 8 and a ST of 10° BTDC at 1400 rpm. As can be seen from the figure, an increase in the methanol ratio results in an increase of bte proportionally. This variation outcome on the improving combustion efficiency is especially due to the presence of oxygen in methanol as mentioned above. Variations of bte values with respect to CR were given in Figure 5c. As expected, bte values increase with an increasing CR for the blend and gasolines, except for the base gasoline. A lower knock resistance of base gasoline compared to other gasolines and blends causes the reduction of bte as a result of the knocking combustion, as mentioned above. The blends gave higher bte with an increasing CR because of an improving fuel octane rating. The leaded and unleaded gasolines also provided improvements in bte because of their higher octane rating. Variations of bte values with ST were given in Figure 5d for the fuels and fuel blends. As is known, increases in ST beyond an optimum value lead to knocking combustion gradually. In this study, this tendency was observed at spark timings higher than 10° BTDC, especially

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for regular and leaded gasolines and the M5 blend. There were no important reductions in bte values obtained with unleaded gasoline and other blends. It was also observed from Figure 5 that the maximum increment in bte was gained with the M20 blend. The increments in bte obtained with the M20 blend are about 16.5, 15, and 6.7% compared to those for base, leaded, and unleaded gasolines, respectively.

5. Conclusions

From the results of the outlined study, the following conclusions can be drawn: (1) Blending of methanol with base gasoline resulted in an increase in the AEC and made the inducted fuel−air mixture leaner. (2) Methanol−gasoline blends gave higher bmep values compared to those base, leaded, and unleaded gasolines, generally. The maximum improvement in bmep was obtained with the M5 blend for a CR of 8 and a ST of 10° BTDC along the entire tested speed range. Furthermore, the differences between the variations of the bmep for the M5 blend and the other blends became noticeable especially for higher speeds. (3) Methanol addition to base gasoline improved the bte almost at a linear character with respect to blending ratios. Thus, for the present study, the maximum bte values were obtained with the M20 blend for all of the test conditions. The best performer among the pure fuels is unleaded gasoline. The worst performance, on the other hand, was obtained with base gasoline among the pure fuels and blends. Increases in the compression ratio increases the brake thermal efficiencies for all tested fuels and blends, except for base gasoline. The M20 blend is also the best performer along the entire range of spark timings. (4) Although the variation of bsfc values was not remarkable among the pure fuels and blends, the cost of the blends are too high and linearly increase with an increase in the blending ratio of methanol because of the high methanol prices in Turkey. This makes the methanol blending to gasoline infeasible with the current price of methanol in Turkey.

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Nomenclature

AEC = air excess coefficient (dimensionless)
AFR = air−fuel ratio (kg of air/kg of fuel)
bmep = brake mean effective pressure (kPa)
bsfc = brake-specific fuel consumption (kg of fuel kW^{-1} h^{-1})
bte = brake thermal efficiency (%)
f = price of unit volume of fuels ($/L)
F = cost of fuel or fuel blends per kW h ($ kW^{-1} h^{-1})
LHV = lower heating value (kJ/kg)
M_d = torque (N m)
n = engine speed (rpm)
N_e = brake power (kW)
P_0 = ambient pressure (MPa)
ST = spark timing (deg)
T_0 = ambient temperature (K)
U = uncertainty (%)
x = volume percent of fuel in the blend (%)
X_{hum} = humidity correction factor (dimensionless)

Greek Letters

ρ = density (kg/m^3)
ω = angular speed (s^{-1})

Subscripts

s = stoichiometric

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