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Article

Oxygenated fuels blending effects on gasoline engine performance and emissions: An experimental study

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Abstract: Alternative fuels have the potential to reduce exhaust emissions in the transportation sector. In this study, the effects of oxygenated fuels on the performance and emissions of a gasoline single-cylinder spark-ignition engine have been investigated experimentally. Experiments were conducted using a DIDACTA-T85 testbed under full load conditions and variable engine speed. Performance tests were performed by measuring the brake torque, brake power, brake mean effective pressure (BMEP), brake specific fuel consumption (BSFC), and brake thermal efficiency (BTE). The tested fuel blends were G0, E10, A10, and M10. G0 represented the base fuel and pure gasoline. E10, A10, and M10 were represented by a 10% volume of ethanol, acetone, and methanol in gasoline respectively. Results showed that M10 produced better engine performance in terms of brake torque, brake power, and BMEP, while E10 performed better results in terms of BSFC and BTE. A10 gave the lowest value in NOx emission at all engine speeds. On the other hand, it increased the NOX emission for E10 and M10 blends. This study showed that oxygenated fuel blends significantly reduced carbon monoxide emission at all engine speeds whereas carbon dioxide emission was higher at the highest engine speed.

Keywords: engine; gasoline; oxygenated fuel; blend; experimental study.

1. Introduction

Nowadays, climate change and global warming are the most common issues that require urgent solutions [1]. It is vital to focus on these problems as they directly impact human health and the continuity of life on earth [2]. Air pollution is the cause of emissions produced by the combustion of fuels in different energy generation sectors. The increasing need for energy made humans exploit all possible resources to generate energy and utilise conventional fuels for transportation, which increased the demand for oil, gas, and water stocks [3, 4]. The international energy agency (IEA) has reported that the global energy demand is set to rise by 4.6 % in 2021, surpassing pre-pandemic levels, because of the increase in global GDP compared to 2019 levels [5]. The surge in GDP pushes global energy demand to increase and subsequently increases greenhouse gas (GHG) emissions such as carbon dioxide (CO_2). Burning conventional fuels such as gasoline and diesel increases CO_2 emissions. CO_2 emissions are causing the earth's atmosphere to warm, leading to changes in the climate as it is seen today. The transportation sector contributes significantly to CO_2 and other GHG emissions because it is almost entirely dependent on conventional fuels [6]. It is well known that petrol-based fuels are energy sources that are

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non-renewable [7,8]. Replacing conventional fuels with renewable fuels in internal combustion engine applications is of great benefit, and many studies have shown great success in their use as alternative fuels [9].

The rapid growth of oxygenated fuels has taken place in the last decades [10]. Due to the high oxygen content in oxygenated fuels, their combustion produces less CO_2 and GHG emissions than conventional fuels [11]. The combined use of alternatives and fossil-based fuels in the form of blends in spark-ignition (SI) engines showed a significant benefit in several studies regarding reducing exhaust emissions and improving engine performances [12]. The use of oxygenated fuels produced from biomass as gasoline replacement is receiving considerable attention. Since oxygenated fuels are derived from agriculture sub-products as a renewable resource, these biofuels showed great benefits by reducing net zero CO_2 emissions and decreasing the dependence on fossil fuels [13].

Many studies have been conducted on the effects of oxygenated fuel blends with gasoline on SI engines' performance and exhaust emissions. However, it has been observed that most of these studies were limited to one or two oxygenated fuel impacts separately. In the present study, we intend to analyse and compare the effects on engine performance (power, mean pressure, efficiency, and fuel consumption) of three oxygenated fuels namely ethanol, methanol, and acetone, at the same time. To observe and analyse these effects, an identical percentage (10%) by volume in pure gasoline was fixed for the three test fuel blends.

This article starts with a review of ethanol, methanol, and acetone production and application in SI engines, considering their effects on engine performance and exhaust emissions. The second part of this article presents the experimental investigation procedure and conditions. Finally, the obtained results of this study are analysed and discussed.

2. Oxygenated fuels production and application in SI engines

Oxygenated fuels have been used as a gasoline additive in SI engines to reduce carbon monoxide (CO) emissions and soot. Many studies have demonstrated that alcohols are a viable option to reduce emissions and improve engine performance [14, 15]. Alcohols (methanol, ethanol, and n-butanol) are organic compounds that contain at least one hydroxyl functional group (-OH) bound. The high oxygen content in alcohols improves combustion efficiency; therefore, the CO level decreases significantly since it is hugely dependent on oxygen content [16-18].

The use of oxygenated fuels is not new. In 1912, Rudolf Diesel tested peanut oil as an alternative fuel [19, 20]. Henry Ford conducted a study on pure ethanol as a fuel replacement. [21, 22]. However, butanol has recently been used as an alternative, in 2005 Ramey [23] used butanol instead of gasoline to make a tour across the USA.

2.1. Production of oxygenated fuels

Based on production procedures, oxygenated biofuels are classified into three groups. First-generation biofuels are produced from feedstocks and consumed as human food by fermentation of carbohydrates. Acetone-Butanol-Ethanol (ABE) fermentation was used, for example, to produce acetone, butanol, and ethanol from biomass considered as a renewable resource like sugarcane, wood waste, corn, and wheat. The second-generation or advanced biofuels are derived from biomasses by various processing ways like a thermochemical process that converts carbon-based biomasses into a synthesis fuel gas. Another procedure known as a biochemical conversion is based on enzymatic hydrolysis of a lignocellulosic resource. The third generation is biofuels produced from algae [24-26].

2.2. Production of oxygenated fuels

Methanol is considered a clean energy resource since it is produced in many renewable ways, such as natural gas, biomass, CO_2, etc. Currently, natural gas represents the highest resource for producing methanol. Many studies have investigated the process route for the production of this oxygenated fuel involving the following three steps, 1) the production of synthesis gas, 2) the conversion of the mixture of syngas into crude methanol, and 3) the purification step using a distillation process.

The synthesis gas is produced by autothermal and steam-reforming natural gas, partial oxidation of methane, and many carbon-based materials [27, 28]. Methanol is also produced from biomass, where the process is based on biomass gasification by thermal conversion, chemical conversion, and biological conversion [29, 30]. As a first step, the biomass is transformed into bio-syngas and then into methanol (Figure 1).

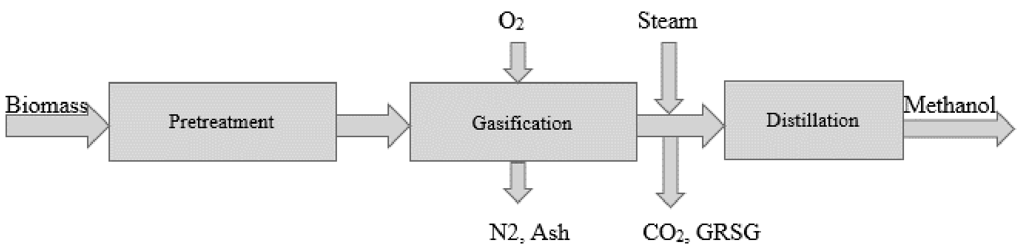

Figure 1. Methanol production from biomass.

Methanol production from CO_2 is showing considerable attention since it is a renewable resource that gives methanol and reduces CO_2 emissions [31, 32]. This process is based on hydrogen production by electrolysis of water and converting it to methanol by adding CO_2, known as catalytic hydrogenation of CO_2. The hydrogenation reaction is:

$$CO_2 + 3H_2 \leftrightarrow CH_3OH + H_2O, \quad (1)$$

2.3. Ethanol production

Ethanol is produced through the hydration of ethylene made from petrochemical feedstocks as given in equation 2.

$$C_2H_4 + H_2O \rightarrow CH_3CH_2OH, \quad (2)$$

where the reaction is carried out with high-pressure steam. Also, it is produced from CO_2 via biological and electrochemical reactions in laboratories (see equation 3).

$$CO_2 + H_2O \rightarrow CH_3CH_2OH + \text{side products}, \quad (3)$$

Another process is fermentation. In this process, the glucose molecules are converted into ethanol and carbon dioxide molecules as shown in equation 4 and equation 5 [33-35].

$$C_6H_{12}O_6 \rightarrow 2CH_3CH_2OH + 2CO_2, \quad (4)$$

$$C_{12}H_{22}O_{11} + H_2O \rightarrow 4CH_3CH_2OH + 4CO_2, \quad (5)$$

2.4. Acetone production

Acetone is produced via the cumene process [36]. In this process, the cumene production is made by alkylated the benzene with propylene. Another old process uses the dry distillation of acetates to produce acetone. Also, it can produce acetone by a synthetic method, like ABE fermentation [37].

2.5. Ethanol in SI engines

Ethanol is an oxygenated liquid hydrocarbon produced from renewable sources such as biomass; it has been used as a fuel for SI engines, for years ago, in the form of blends mixed with gasoline. Many studies showed a great benefit of using ethanol blends in SI engines due to their chemical and physical properties [38]. It is a colourless fuel characterised by the high latent heat of vaporisation and octane number that can allow for a high compression ratio. It contains about 34.8 % oxygen by molecular weight, improving thermal efficiency and reducing exhaust emissions. Table 1 shows the chemical and physical properties of ethanol. There have been many experimental and numerical studies conducted on the influence of using ethanol in SI engines.

Table 1. Chemical and physical properties of ethanol [39].

Parameters	Value
Lower heating value (MJ/kg)	26.8
Density (kg/m^3)	790
Energy density (kJ/m^3)	21.17
Octane number	100
Oxygen content (wt.%)	35
Boiling temperature (°C)	78
Latent heat of vaporization (25°C) (kJ/kg)	904
Self-ignition temperature (°C)	420
Stoichiometric AFR	9.0
Laminar flame speed (cm/s)	~48

Run et al. [40] investigated the effect of ethanol-gasoline blends on the characteristics of combustion and soot formation for a direct-injection SI engine experimentally. They found that achieving desirable combustion with less soot formation for lower-level ethanol blends is possible. Zhanming et al. [41] studied the combustion process and cycle-by-cycle variations of SI engine powered by methanol, ethanol, and n-butanol. This study showed that the indicated mean effective pressure was distributed in a wider range with the increase in air-fuel ratio (λ) for the engine fueled with ethanol and n-butanol. It is not the same for the case of methanol, where the indicated mean effective pressure was distributed in a narrow range under all conditions of λ. The results showed a significant increase in the coefficient of variation of indicated mean effective pressure (COVIMEP) of both methanol, ethanol, and n-butanol with increasing in λ.

Da Costa et al. [42] conducted an experimental study to analyse the effect of natural gas-hydrous ethanol dual-fuel on the performance, emissions, and combustion characteristics in SI engine with internal exhaust gas recirculation. The ethanol dual-fueled and compressed natural gas (CNG) port-injected at 4 bars. At a stoichiometric λ and 1800 rpm engine speed, they found an improvement in fuel conversion efficiency in dual-fuel configuration but an increase in nitrogen oxides (NO_x) emissions compared to CNG-only operation.

Gao et al. [43] investigated the impact of ethanol addition in flame and exhaust soot in a direct-injection SI engine with ethanol blending ratios ranging from 0-60%. A transmission electron microscope was used to detect the internal structures of in-flame and exhaust soot particles. They found a significant reduction in number counts and projection area for both the in-flame and exhaust soot particles with an increasing ethanol blending ratio. For all ethanol blending ratios, the projection areas and the number counts of exhaust soot showed a lower value than those of the in-flame soot—the reduction of engine-out soot due to the suppressed soot formation within the flame.

Setyono and Arifin [44] investigated the effect of ethanol-gasoline blends on performances in the last generation of SI engine. In this study, a blend of ethanol-gasoline containing 25%, 35%, and 45% of ethanol in SI engines instead of pure gasoline. The engine speeds was ranging from 4000-9000 rpm, and a spark plug no ground-electrodes type was used in this study. They found that the high engine performances and the less specific fuel consumption were obtained using an ethanol-gasoline blend of G45. Catapano et al. [45] conducted an experimental study on the influence of ethanol-blended and dual-fueled gasoline on soot formation and particulate matter emissions in a small-displacement SI engine. This study showed that the effect of ethanol on soot formation and particles emission depends on ethanol fuel properties, engine configuration, and operating conditions.

Sakai et al. [46] investigated the impact of ethanol blending on particulate emissions from a direct-injection SI engine. They found that increasing ethanol content leads to a decrease in engine-out particulate despite changes in fuel properties and that particulate results can be affected by engine operating history, which could have implications for research and real-world applications.

Al-Hassan et al. [47] investigated the effect of ethanol-unleaded gasoline blends on engine performance and exhaust emission. The study showed that blending unleaded gasoline with ethanol increases brake power, torque, volumetric and brake thermal efficiencies, and fuel consumption, decreasing the brake-specific fuel consumption and equivalence air-fuel ratio. They found that CO and hydrocarbon (HC) emissions concentrations in the engine exhaust decrease while CO_2 emissions increase. This study showed that 20 vol.% ethanol in a fuel blend provided the best results for all measured conditions.

Fatouraie et al. [48] investigated an experimental study on the effect of ethanol/gasoline blends on the in-cylinder formation of particulate matter (PM) and fuel spray characteristics. They found a significant reduction in in-cylinder soot formation with the higher ethanol content in the fuel, regardless of fuel injection timing. Fuel impingement was a significant factor affecting the level of PM emissions. Retarded fuel injection timing reduced the PM formed in-cylinder for the two fuel blends and the baseline gasoline. The authors concluded that higher coolant temperatures reduced liquid fuel on piston and cylinder wall surfaces and reduced in-cylinder PM formation. This study showed that ethanol blends can be used to reduce PM formation in a direct-injection SI engine at varying levels of ethanol concentration in the fuel.

Szybist et al. [49] investigated the effect of ethanol blends and engine operating strategies on a light-duty SI engine's PM emissions. The results showed that when direct injection fueling was used for gasoline and E20, the particle number emissions increased by 1-2 orders of magnitude compared to port fuel injection fueling, depending upon fuel injection timing. On the other hand, when a direct injection was used with E85, the particle number emissions remained low and comparable to PFI fueling. They concluded that, by using E85, the efficiency and power advantages of direct injection fueling can be gained without generating the increase in particle emissions observed with gasoline and E20.

Qian et al. [50] investigated an experimental study on engine performance and octane on-demand studies of a dual-fuel SI engine with ethanol/gasoline surrogates as fuel. They found a prolongation in flame development duration (FDD) and rapid combustion duration (RCD) when direct injection of toluene fuel with a research octane number of 90, and with the increase of ethanol injection ratio while engine maximum in-cylinder pressure and temperature decreased gradually. The unregulated emissions (ethane, isopentane, cyclohexane, propylene, isobutene, aromatic) decreased gradually with the increase of the proportion of ethanol injection. This study showed that there was a significant increase in in-cylinder pressure and heat release rate for dual fuel configuration with the advance of the spark timing.

2.6. Methanol in SI engines

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Methanol is an oxidised hydrocarbon and is characterised by a high auto-ignition temperature and flash point compared to gasoline, making it safer for transportation and storage. Methanol was considered an alternative biofuel for SI engines [51, 52]. Many studies showed the benefit of using methanol in SI engines. It is less expensive in production than ethanol fuel, but it is characterised by its high toxicity and low energy density [53]. Table 2 below shows the chemical and physical characteristics of methanol.

Table 2. Chemical and physical properties of methanol [54,55].

Parameters	Value
Lower heating value (MJ/kg)	20.09
Density (kg/m^3)	792
Energy density (kJ/m^3)	21.17
Octane number	108.7
Oxygen content (wt.%)	49.93
Boiling temperature (°C)	78
Latent heat of vaporization (25°C) (kJ/kg)	920
Self-ignition temperature (°C)	423
Stoichiometric AFR	6.4
Laminar flame speed (cm/s)	~52

Several studies demonstrated the benefit of using methanol in SI engines, alone or blended with gasoline and other alternatives (ethanol, butanol, and acetone).

Zhanming et al. [41] conducted an experimental study on the combustion process of an engine fueled with pure methanol, ethanol, and n-butanol; they reported that the flame development and flame propagation periods of methanol were shorter than those of ethanol and n-butanol and methanol characterised by a better lean-burn capability, high burning rate and lower cycle-by-cycle variations in comparison with the other tested fuels. Elfasakhany [56] has investigated the effect of ethanol-methanol-gasoline blends on the performance and emissions of SI engine. This study showed that methanol-gasoline blends led to the highest volumetric efficiency and torque, while ethanol-methanol-gasoline blends showed moderate volumetric efficiency, torque, and brake power. Moreover, gasoline produced the lowest volumetric efficiency, torque, and brake power. On the other hand, methanol-gasoline blends provided the lowest emissions of CO and unburned HC (UHC) emissions in comparison with other tested blends, and ethanol-methanol-gasoline blends generated a moderate emission level, lower than ethanol-gasoline. Pure gasoline blends produced the highest emissions level. Hu et al. [57] studied the effects of methanol-gasoline blends on the characteristics of combustion in SI engines. This study showed that adding methanol to gasoline can improve engine combustion, whereas increasing methanol content in gasoline tends to increase IMEP and improve flame development and fast-burning period. Significant decreases in CO and UHC emissions were seen when the methanol fraction was increased.

Yanju et al. [58] experimented with an SI engine using methanol-gasoline blends as an alternative, the tested blends were M10, M20, and M85. Results showed that adding methanol to gasoline improved engine performance, while the blends ratio slightly affected it. Also, increasing methanol in gasoline conduct reduced CO and NOx emissions, where M85 showed the best results. At the same time, UHC emissions were increased with an increase in methanol content in gasoline. Verhelst et al. [59] conducted a review study on the use of methanol in an internal combustion engine. They analysed deeply different studies that have been investigated on this topic. They affirmed that methanol is a viable option as an alternative fuel. Abu-Zaid et al [60] have performed experimental studies on the effect of methanol addition on the performance of SI engine. This study showed that M15 was conducted for the best results in engine performance. Ahmed [61] studied the effect of methanol-gasoline blends on SI engines. This study showed that engine performances improved with increasing methanol content in gasoline and M10 conducted for the best results in reducing exhaust emissions.

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Liu et al. [62] studied methanol-gasoline blends in SI engines. This study showed an improvement in combustion characteristics with increased methanol content in gasoline and a decrease in CO and UHC emissions. The unburned methanol emission increased with increasing methanol fraction, engine speed, and load. Qi et al. [63] used two blends of methanol, ethanol, and gasoline to characterise the SI engine's properties, performances, and the characteristics of combustion of tested blends. The blends were M10 and M25, which M10 formed by gasoline with 8.5 vol% methanol and 1.5 vol% ethanol, and M25 containing gasoline with 19 vol% methanol and 6 vol% ethanol. Results showed that the specific fuel consumption (SFC) increased in the case of M25 compared with pure gasoline and M10, where it was almost the same at full load and all engine speeds. M25 was conducted to the highest value of HC emissions and the lowest value of NO_x emission for all engine loads compared to pure gasoline and M10. CO emissions showed the highest value in the case of pure gasoline at low and moderate loads, while, under high loads, the highest value was seen in the case of M25.

Sharudin et al. [64] performed an experimental study on the effect of iso-butanol on SI engine fueled with methanol-gasoline blends. The tested blends consisted of a lower ratio of methanol-gasoline M5 with the addition of iso-butanol at a different ratio (5 to 15%) compared with pure gasoline. Results showed an improvement in engine performance with M5B15. For all tested blends, fuel consumption was higher than that of pure gasoline. CO and HC decreased significantly in the case of M5B15, while NOx and CO2 recorded the highest value. The work concluded that iso-butanol additives significantly improve engine performance and combustion characteristics when blended with a lower ratio of methanol-gasoline.

Yilmaz and Taston [65] studied the addition of hydrogen to methanol-gasoline blends in SI engine. The tested blends were M5, M10, and M15 with hydrogen addition in different ratios (3%, 6%, 9%, and 15%). Compared to gasoline, results showed an increase in brake specific fuel consumption (BSFC) by 26% and a decrease in thermal efficiency by 10.5%, by increasing the methanol content in gasoline. BSFC decreased by 4%, and thermal efficiency increased by 2% when adding hydrogen to methanol-gasoline blends. This study showed a significant decrease in exhaust emissions (CO, HC, and CO_2) by adding hydrogen to methanol-gasoline mixtures while NO_x increased.

2.7. *Acetone in SI engines*

Biofuels such as acetone, a colorless liquid with a characteristic odor and high volatility, can be produced by fermentation of biomass such as sugar beet, sugarcane, wood, and degermed corn [66-68]. Using acetone as fuel for SI engines has advantages over pure gasoline, such as improvement in engine performance with increasing acetone content in the blends as investigated by Elfasakhany [69] in an experimental study where the blended fuels were formed by adding 3 to 10 vol% of acetone into gasoline. The chemical and physical properties of acetone are summarised in Table 3 below.

Table 3. Chemical and physical properties of acetone [39].

Parameters	Value
Lower heating value (MJ/kg)	29.6
Density (kg/m^3)	790
Energy density (kJ/m^3)	23.38
Octane number	117
Oxygen content (wt.%)	27
Boiling temperature (°C)	56.2
Latent heat of vaporization (25°C) (kJ/kg)	518
Self-ignition temperature (°C)	465
Stoichiometric AFR	9.5
Laminar flame speed (cm/s)	~34

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The addition of acetone in gasoline has attracted the attention of researchers because it shows a great benefit in improving combustion performance and reducing exhaust emissions, due to its high volatility [70]. Elfasakhany [71] carried out an experimental study on the use of ABE blends, n-butanol, and isobutanol to compare their effect on the SI engine's performance and exhaust emissions. This study showed that acetone blends produced the lowest CO and UH emissions and a moderate performance among all test blends. Li et al. [72] affirmed that ABE could be used as a promising alternative fuel in SI engine based on an experimental study, which showed that ABE could reduce emissions like CO and HC without significant loss in engine performance compared with pure gasoline.

3. Materials and Methods

3.1. Engine specifications

A single-cylinder SI engine powered by alternative fuel blends was tested under full load conditions at variable engine speed using the DIDACTA-T85 engine test bed. Table 4 shows the engine specifications and Figure 2 shows the tested engine.

Table 4. Engine specifications.

Parameters	Value
Cycle (stokes)	4
Cooling type	Water
Bore (mm)	80.95
Stroke (mm)	69.85
Capacity (cc)	360
Compression Ratio	8:1
Power (bhp)	5

Figure 2. Single-cylinder SI engine on a test bed.

3.2. Fuel blends preparation

This work focused on the effect of adding a low quantity of oxygenated fuels in pure gasoline on the performance of SI engine. The tested blends were G0, E10, A10, and M10, where G0 represents pure gasoline, and E10, A10, and M10 represent the ethanol-gasoline, acetone-gasoline, and methanol-gasoline blends respectively. The fuel blends' specifications are shown in Table 5. Each fuel blend was prepared and mixed just before each experiment.

Table 5. Chemical and physical properties of gasoline blends [39,73].

Parameters	Value
Chemical formula (x = 5-10, y = 12-22)	C_xH_y
Lower heating value (MJ/kg)	41
Density (kg/m^3)	715-765
Energy density (kJ/m^3)	32.20
Octane number	92
Oxygen content (wt.%)	0
Boiling temperature (°C)	25-215
Latent heat of vaporization (25°C) (kJ/kg)	380-500
Self-ignition temperature (°C)	~300

Table 6 shows the lower heating value (LHV) for each blend which was calculated based on equation 6.

Table 6. LHV of gasoline blends.

Blend	LHV (MJ/kg)
G0	41.00
E10	39.57
A10	39.86
M10	38.89

$$(LHV)_b = \Sigma\ (\varrho_i \upsilon_i / \varrho_b \upsilon_b)\ LHV, \quad (6)$$

Where symbol "b" denotes fuel blend, symbol "i" denotes the initial value of the gasoline, "ϱ" is the density of fuel, and "υ" is the volume of fuel.

3.3. Experimental set-up

The DIDACTA-T85D test bed consisted of a control unit panel, a dynamometric unit, a cooling circuit, and a fuel supply system. For each test, the engine speed was varied from 1000-3000 rpm and the engine wall's temperature was fixed between 75 °C and 85 °C at full load condition. Figure 3 shows the schematic diagram of the experimental setup.

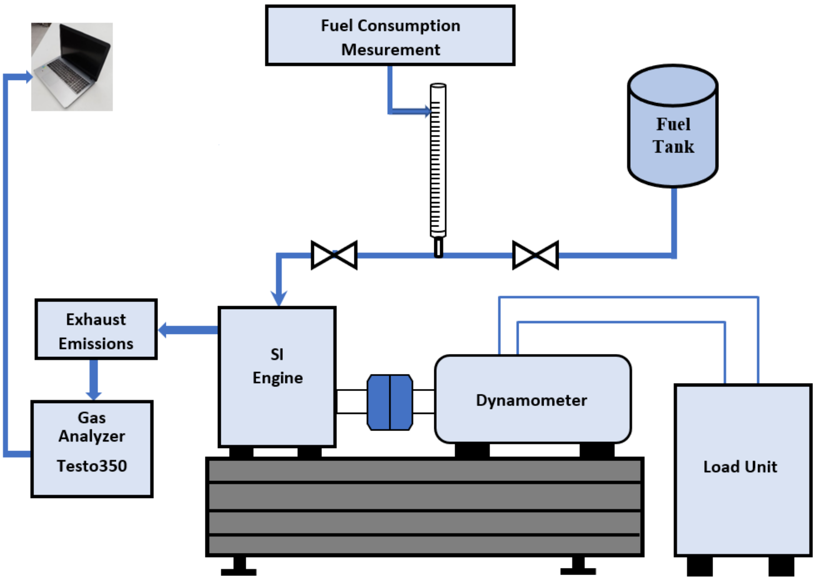

Figure 3. Schematic diagram of the SI engine on the DIDACTA-T85D test bed.

All the measured data was logged after ten minutes of engine operation. An average of three test data was used for this study. Measurements of CO, CO_2, and NOx emissions were performed under full load conditions and at an engine speed ranging from 1000-3000 rpm with 500 rpm intervals. The gas analyser TESTO 350 was used for emissions measurements. All measuring types of equipment and sensors were calibrated to the manufacturing standards. The engine test rig is shown in Figure 4.

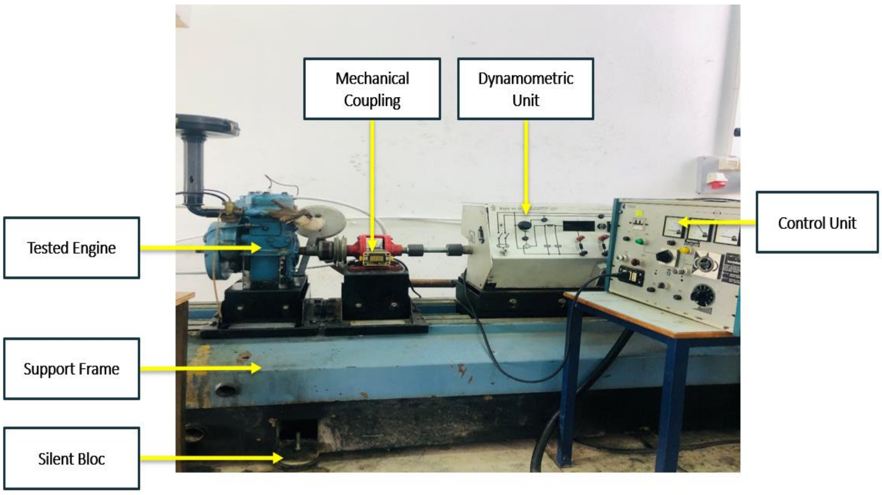

Figure 4. Engine test bench.

4. Results

The effects of various oxygenated fuels on the performance of a single-cylinder SI marine engine are presented and discussed in this section. Pure gasoline (G0) was considered the base fuel in this comparative study.

4.1. Effects on engine performance

4.1.1. Brake torque

The results of adding oxygenated fuels to gasoline on brake torque are presented in Figure 5. It was observed that adding oxygenated fuels to gasoline increased brake torque due to the enhancement of combustion quality by increasing the equivalence λ. Also, the results showed a significant improvement in brake torque at the highest applied speed (Figure 5). The graph reveals a synergistic effect of oxidant and speed combination upon brake torque. Among oxidative combinations of gasoline, the M10 performance was superior to others at all tested engine speeds. This superiority was more pronounced at the lowest and highest engine speeds.

These results are aligned with the results in the literature [56]. The highest brake torque value obtained for methanol followed by ethanol blends led to the conclusion that this effect was mainly due to the high octane numbers of oxygenated fuels compared to gasoline.

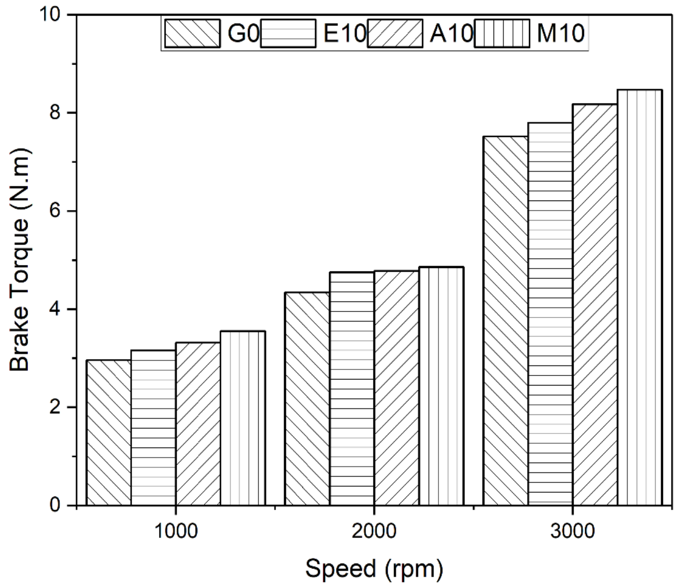

Figure 5. Brake torque vs. engine speed.

4.1.2. Brake power

Figure 6 presents the values of the brake power of four fuel blends as a function of engine speed. Similar results of brake power for all fuel blends were noted at low engine speed (1000 rpm) and medium (2000 rpm) engine speed. The similar performance of the brake power between all tested fuel blends at low engine speed can be explained by the fact that the effect of the LHV of the tested fuel blends is more evident than their octane numbers. On the other hand, oxygenated fuel blends not only produced a higher brake power than pure gasoline at high speed (3000 rpm) but a promising difference within alternative fuel blends was observed.

It was also observed that M10 provided a higher brake power than A10, and E10, at all engine speeds particularly at 3000 rpm. This can be explained by the fact that M10 was characterised by the highest value of density, oxygen content, and octane number followed by A10, E10, and G0.

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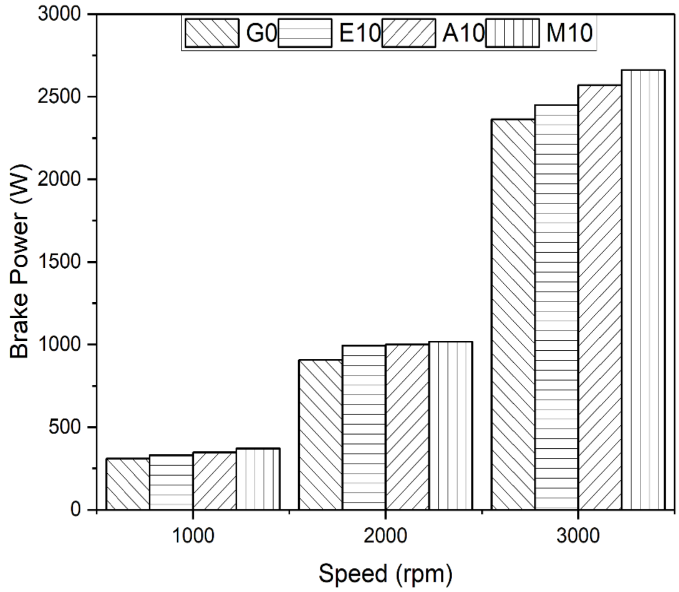

Figure 6. Brake power vs. engine speed.

4.1.3. Brake mean effective pressure

Brake mean effective pressure (BMEP) for four fuel blends is shown in Figure 7. It can be observed that oxygenated fuel blends increased the BMEP value of the SI engine. M10 showed the highest BMEP values throughout all engine speed ranges and G0 produced the lowest BMEP values. Acetone was characterised by a high-octane rating than ethanol and pure gasoline, thus A10 produced high BMEP than E10 and G0 for all engine speeds. G0 provided the lowest BMEP value due to its lower octane rating. BMEP value is directly proportional to brake torque. Hence, the same effects were observed for the different fuel blends.

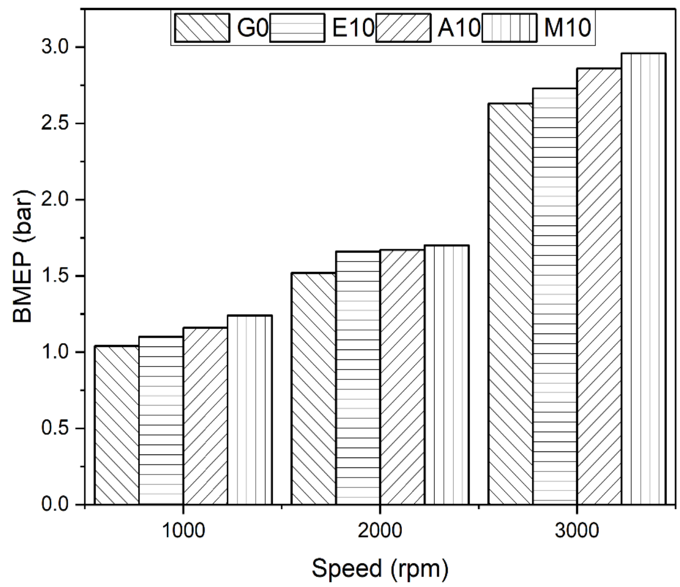

Figure 7. BMEP power vs. engine speed.

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4.1.4. BSFC

Figure 8 shows the effect of oxygenated fuel blends on BSFC. Adding ethanol, methanol, and acetone in gasoline significantly decreased the engine fuel consumption except for A10 at high engine speed. For all engine speeds, A10 showed the highest value of BSFC among oxygenated fuels. This can be explained by the fact that A10 was characterised by the lowest values in oxygen content and flame speed, and the highest autoignition temperature, which increased the engine fuel consumption.

However, E10 led to the lowest BSFC values, where E10 was characterised by a lower heating value, a higher heat of vaporisation, and more oxygen content than G0 and A10. On the other hand, using M10 (characterised by the lowest heating and the highest heat of vaporisation values), a low value of BSFC was obtained comparatively to G0 and A10. At high engine speed, A10 showed the highest BSFC value.

In terms of relative enhancement, E10 performed the best BSFC values at all engine speeds range. For example, at 2000 rpm, adding 10% of ethanol to gasoline has decreased the BSFC by 25%.

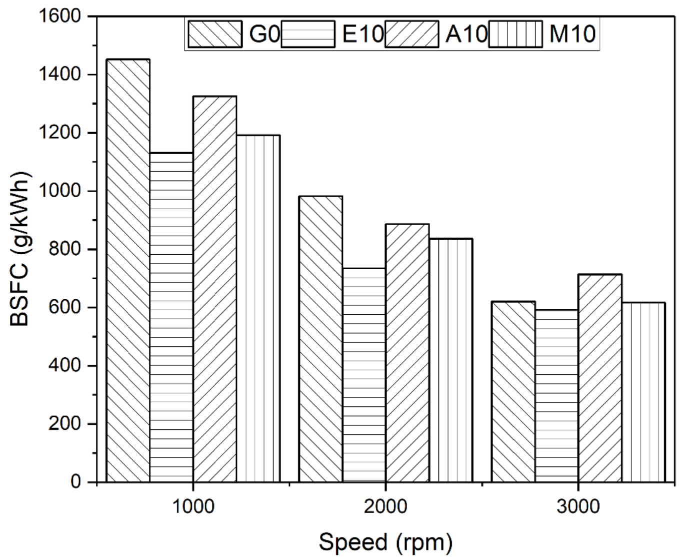

Figure 8. BSFC power vs. engine speed.

4.1.5. Brake thermal efficiency

Figure 9 shows the effect of using oxygenated fuels in SI engines on brake thermal efficiency (BTE). E10 produced the highest BTE at all engine speeds, except at 1000 rpm (lower than M10). This was because, at low speed, the high oxygen content and flame speed of M10 had a preponderant effect on BTE. As a result, an increase in BTE by 33 % compared to G0, was observed. Whilst, at high and medium engine speeds, the combined effects of low heating value, high evaporation, and good oxy-gen content of ethanol were more influencing on BTE by an enhancement ranging from 9-42 % obtained at 2000 rpm and 3000 rpm, respectively.

The present study demonstrated that, generally, oxygenated fuels offer higher BTE than gasoline. This effect is due to the excellent fuel characteristics of alcohols, such as higher latent heat of vaporisation, octane number, and oxygen content.

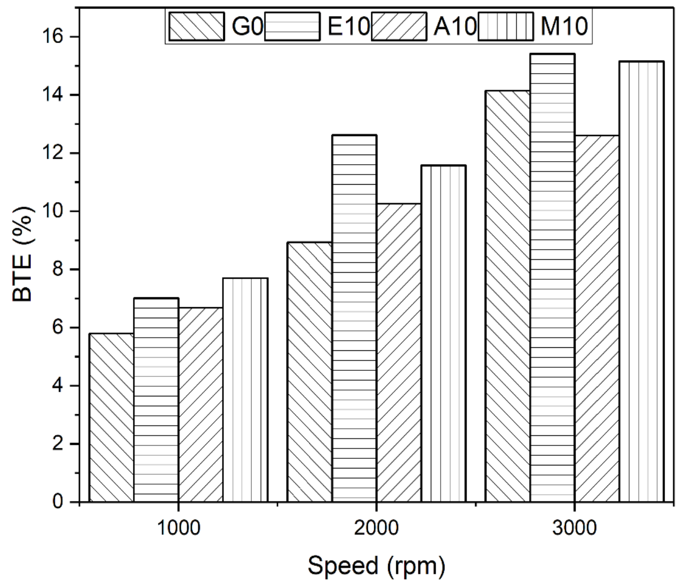

Figure 9. BTE power vs. engine speed.

4.2. Effects on exhaust emissions

4.2.1. CO emissions

Pure gasoline is a hydrocarbon that contains only hydrogen and carbon atoms. It is characterised by a high heating value compared to other tested blends. On the other hand, the tested fuel blends contained hydrogen, carbon, and oxygen atoms. Oxygen improves combustion characteristics and reduces CO and UHC emissions since they are dependent on oxygen content. Figure 10 presents the CO emissions as a function of engine speeds for the four blended fuels. Results showed a reduction in CO emissions for oxygenated fuels, comparatively to neat gasoline due to the presence of oxygen atoms in the tested fuel blends. A slight decrease in CO emission was noticed at low and medium engine speeds, while, at high engine speed, the decline was more pronounced. This result could be attributed to the more homogeneous mixture, at high engine speed, giving better combustion characteristics.

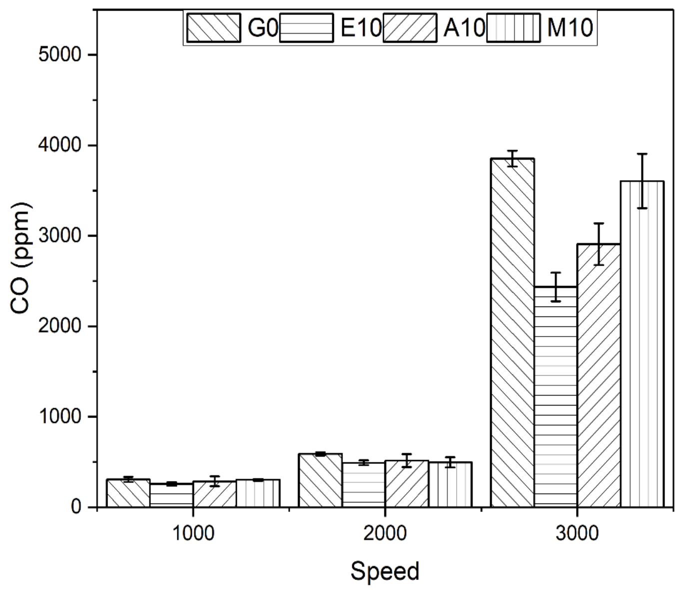

Figure 10. CO emissions vs. engine speed.

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E10 produced the lowest value in CO emissions. This could be attributed to the combined effects of the LHV and oxygen contents values of ethanol comparatively to methanol and acetone. Thus, it has better combustion characteristics and subsequently reduced CO emissions. A10 has lower CO emissions than M10, which was significant at high engine speed. This could be attributed to the higher LHV of ace-tone compared to methanol. At medium engine speed, the difference in CO emissions between all oxygenated fuels was insignificant.

4.2.2. CO_2 emissions

Figure 11 shows an opposite trend of CO_2 emissions than CO emissions for all fuel blends, due to the chemical oxidation of CO into CO_2 in the presence of O2 during the combustion reaction. Results showed that a low quantity (10%. vol) of oxygenated fuel in gasoline decreased CO_2 levels at low and medium engine speeds. At high engine speed, it was noticed an increase in CO_2 emissions for E10 and M10, while A10 produced a similar result to G0. These results were attributed to the beneficial effect of oxygen in the tested fuel blends, which developed better combustion characteristics. At high engine speed, the effect of LHV was more evident to improve combustion characteristics.

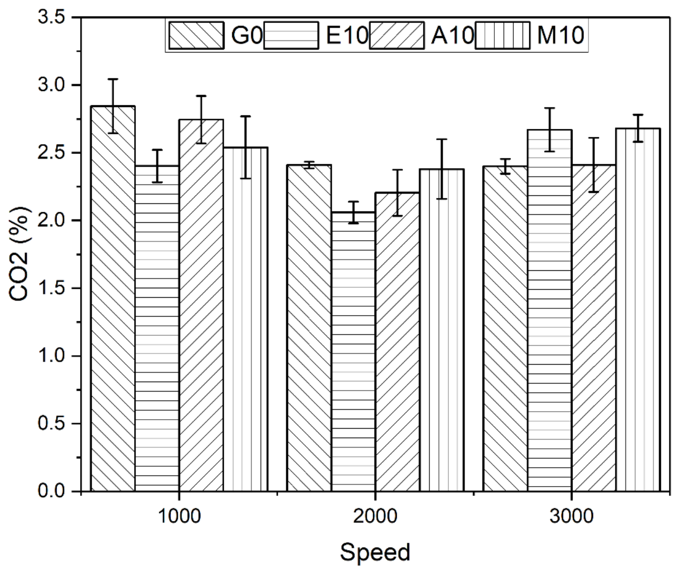

Figure 11. CO_2 emissions vs. engine speed.

4.2.3. NO_x emissions

Figure 12 shows that E10 and M10 have higher NO_x emissions compared to A10 and G0. These differences were because ethanol and methanol contained more oxygen than acetone and gasoline and have higher octane ratings, resulting in a higher combustion temperature. The higher levels of NO_x emissions for E10, at all engine speeds, could be attributed to the high heat release rate of ethanol compared to other blends. A10 produced the lowest NO_x emissions at all engine speeds. This was attributed to the beneficial characteristics of acetone, which features low oxygen content and high LHV, resulting in improved combustion characteristics.

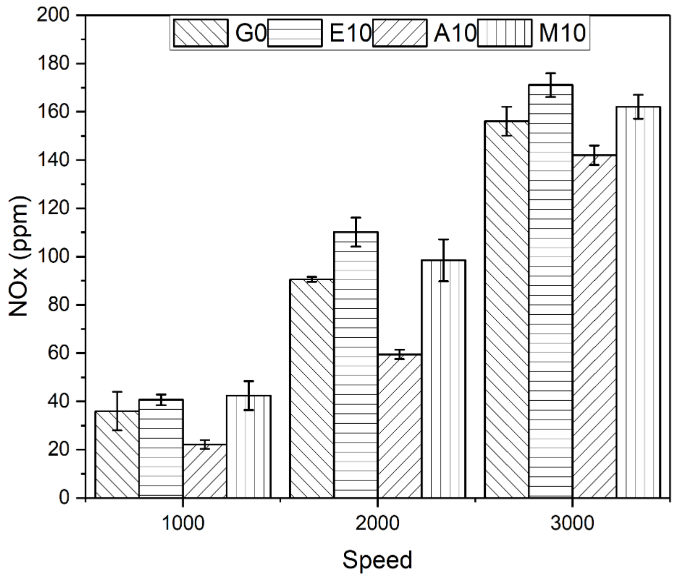

Figure 12. NO_x emissions vs. engine speed.

5. Conclusions

The effect of oxygenated fuels in gasoline for SI engine was successfully validated through experimental setup. The experimental results have demonstrated that:

- adding oxygenated fuels to gasoline in low quantity improved the engine performance;
- methanol blend provided the best values in engine torque, power, and BMEP at all engine speeds. The enhancement can reach up to 20 % at low engine speed;
- at medium and high speeds, the ethanol blend reduced BSFC (by 25 % at 2000 rpm) and improved BTE (by 41 % at 2000 rpm). At low speed, the methanol blend produced the best BSFC values;
- oxygenated fuels reduced CO and CO_2 emissions, while E10 and M10 increased NO_x emissions;
- the lowest NO_x emissions were obtained for A10 at all engine speeds;
- oxygenated fuels could be used as fuel additives in SI engines without any technical modifications.

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