Impact of Denatured Anhydrous Ethanol–gasoline fuel blends on a Spark-Ignition engine

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Abstract

Alcohols are a potential alternative fuel because of their renewable bio-based sources. Since the nineteenth century alcohols have been used as an alternative fuel in gasoline engines. Investigations into performance and emissions relating to the use of denatured anhydrous ethanol (DAE) (94.8% ethanol + 5% methanol + 0.2% water) blends with gasoline are discussed in this paper. Tests were carried out at half throttle and under variable speed conditions for a speed range of 1000 to 4000 rpm with various blends of DAE-gasoline fuel on a 1.6 liter 4-cylinder gasoline engine. It was observed that DAE has a significant positive effect on the performance of the gasoline engine. The results showed that blending gasoline with DAE slightly increases the torque, brake power, volumetric efficiency and brake power with higher brake specific fuel consumption. In addition, DAE reduces CO, HC and NOx emission. In terms of investigated parameters, up to 50% blends with gasoline have been found to be a promising fuel for gasoline engines.

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1. Introduction

It is an undeniable truth that the storage of energy in the earth's crust is diminishing day by day, which is bringing about an exasperating situation with respect to the energy crisis and environmental pollution. The massive usage of that energy will escalate the exhaustion of finite fossil fuels. Petroleum-based fossil fuels presently provide the major portion of energy. However, their sources are limited in this earth. The World Energy Forum has predicted that fossil-based oil, coal and gas reserves will be exhausted in less than another 10 decades [1]. Due to the increasing usage and detrimental environmental effects of these fossil fuels, researchers are motivated to search for renewable sources [2, 3]. Furthermore, the burning of petroleum derived fuel generates emissions that seriously affect both the environment and human health. In particular, the burning of fossil fuels is a main contributor to the increase in carbon dioxide (CO_2) emissions, which in turn aggravates global warming [4, 5].

In the quest for renewable sources, researchers have tested many alternative sources. Among them bio-ethanol is by far the most widely used biofuel and has been used in transportation since the nineteenth century [6-8]. Research on the use of alternative fuels such as methanol and ethanol and their blends in spark ignition engines is being intensively proposed because of their potential for low exhaust emissions[9-11]. A lower percentage of ethanol in ethanol-gasoline blends can be used in unmodified engines without any engine modification. Higher percentage blends can also be used with some modification of the engine. Using ethanol-gasoline blends as a fuel, significantly reduce the use of gasoline as well as exhaust emissions[12].

Ethanol has a higher latent heat of evaporation as well as octane number than that of gasoline and it contains 34.7% oxygen by weight. As a result of these properties, ethanol enhances the engine performance and lowers emissions. Liu et al. [13] used gasoline, 10% and 20% ethanol in gasoline blends in a three-cylinder port fuel injection gasoline engine. The addition of ethanol increases the oxygen content in the fuel, thus increasing the ethanol fraction in the gasoline results in lower hydrocarbon (HC), carbon dioxide (CO_2) and NOx emissions than gasoline. Venugopal et al.[10] measured the performance, emission and combustion characteristics of a port fuel-injected engine with 10% hydrous ethanol by volume in gasoline and compared the results with gasoline. Hydrous ethanol produced higher torque and thermal efficiency and a lower HC at 25% throttle. The researchers attributed this to the presence of oxygen in the fuel and the higher combustion rate. Costa and Sodré [14] investigated the performance and emission of hydrous ethanol (6.8% water content) and a 78% gasoline-22% ethanol blend (E22) with varying speeds. They found hydrous ethanol produced higher break thermal efficiency (BTE) and break specific fuel consumption (BSFC) than E22 over the entire speed range but higher torque and break mean effective pressure (BMEP) were observed for high engine speeds. Hydrous ethanol reduced CO and HC emissions but increased CO_2 emission.

Koç et al. [8] experimentally investigated the performance and pollutant emissions characteristics of an unleaded gasoline-ethanol blend with two different compression ratios. The results showed that the ethanol addition to unleaded gasoline increases the engine torque, power and fuel consumption and reduces CO and HC emissions. They also found the ethanol–gasoline blends allowed the use of a higher compression ratio (CR) without the occurrence of knocking. Turner et al. [15] used different blending-ratios of bio-ethanol from 0 to 100% with gasoline on a direct injection spark ignition (SI) engine. It is seen that the addition of ethanol in gasoline reduced the engine-out emissions such as CO, HC and NOx and improved engine efficiency. They attributed these benefits to the addition of bio-ethanol, which modifies the evaporation properties of the fuel blend and the presence of oxygen within bio-ethanol molecules.

Like ethanol, methanol also has the potential to draw attention. It can be used with gasoline because of its simple chemical structure, high octane number, high oxygen content and faster flame propagation speed. Yanju et al. [16] used 10%, 20% and 85% methanol by volume with gasoline to investigate the effect of methanol-gasoline blends on the performance of and emissions from a port fuel injection SI engine. They found an improved BTE with the use of methanol. An increase in the methanol fraction in the blends results in decreased CO emission but increased unburned methanol emission. Liu et al. [17] used methanol-gasoline blends in a three-cylinder port fuel injection SI engine. The results showed that with an increasing fraction of methanol, the engine power and torque decreased; while the brake thermal efficiency improved under Wide Open Throttle (WOT) conditions. An increase in methanol also increases the formaldehyde and unburned methanol emissions, but lowers CO and HC emissions. Abu-Zaid et al. [18] also investigated the effect of a low methanol fraction (15%) addition to gasoline on the performance of a SI engine under wide open throttle and variable speed conditions. According to their study, BTE, BMEP and brake power (BP) increase with the increase in methanol portion in the blend. They attributed the greater volumetric efficiency to the higher latent heat of vaporization of methanol, which largely cools the air in the engine, thus increasing the density of the air and allowing more air in, resulting in a greater mass density of the fuel-air mixture. Latey et al. [19] experimentally investigated the performance, combustion and emissions of a motorcycle engine using 5% methanol with different volume of gasoline-ethanol blends (5%, 10%, 15% and 20% by volume with gasoline). Blends with 5% methanol, 20% ethanol and 75% gasoline showed better performance and combustion with lower emission compared to gasoline.

Almost all the research previously concluded adopted either pure ethanol or pure methanol. So far, few works have been done on denatured ethanol. Therefore, the purpose of this study is to test and analyze the influence of DAE-unleaded gasoline blended fuel on a SI engine performance and exhaust emissions. This target includes testing a gasoline engine fueled with the blends and analyzing brake engine power, torque, brake specific fuel consumption, volumetric efficiency, brake thermal efficiency, and CO, HC, CO_2 and NOx emission.

2. Experimental apparatus and procedure

2.1. Experimental Setup

The engine used in this study was a 1.6 liter 4-cylinder gasoline engine. The engine specifications are listed in Table 1. No modifications were made to the engine. A schematic diagram of the test bed is shown in Fig.1. The engine operating conditions were controlled using an eddy current dynamometer with a maximum braking power of 80kW and maximum speed of 9000 rpm.

Table 1. Specification of the tested engine

Type	**1.6L multi cylinder engine**
Model	GA6D
No. of cylinders	4
Valve mechanism	16-Valve DOHC
Total displacement	1594cc
Bore	78.0 mm
Stroke	83.4 mm
Combustion chamber	Bowl
Max Power	79.4278kW at 5700rpm
Max torque	143.42 Nm at 4500rpm
Fuel system	Multiple port injection

We measured fuel flow rate using a KOBOLD ZOD positive-displacement type flow meter (KOBOLD, Germany). The data were automatically collected using the CADET 10 data acquisition system. Furthermore, the air flow into the engine is measured by a hot-film air flow meter (Type HKM 5, by BOSCH). The exhaust emissions were measured with an "Autocheck 974/5" emission gas analyzer. "Autocheck 974/5" is a portable automobile exhaust gas analyzer that uses single beam, non-dispersive infrared [20] to determine CO, CO_2 and HC concentrations. NOx emissions were measured using the AVL DICOM 4000 exhaust gas analyzer (AVL DiTEST, Austria), where NOx determined by electrochemical measurement detector.

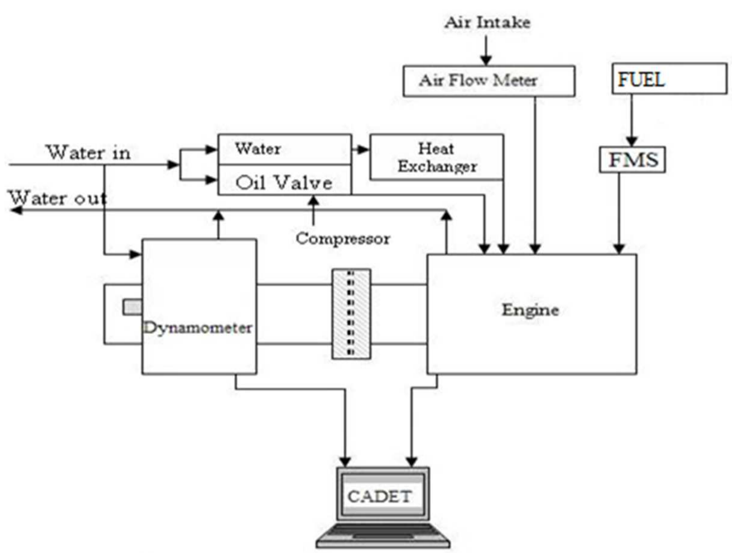

Fig. 1. Schematic diagram of the engine test bed

2.2. Fuel selection

DAE and unleaded gasoline (U97 from Shell, Malaysia) has been used in this study. Anhydrous ethanol means an ethyl alcohol that has a purity of at least ninety-nine percent, exclusive of added denaturants [21]. Denaturants are certain materials added to the ethanol to make it unsuitable for use as a beverage, and the denaturants used are gasoline and toxins such as methanol, naphtha and pyridine [22]. DAE consists of ethanol (purity of 99.7%) of about ethanol 94.8% by volume, methanol of about 5% by volume and the rest is water. In this experiment, fuel properties were measured by implementing various apparatuses, as detailed in Table 2. The value of Fuel RON was provided by the suppliers. Table 3 presents a comparison between the physicochemical properties of gasoline and DAE.

Table 32: Apparatus used for testing fuel properties

Property	Equipment	Manufacturer	Standard method
Density at 15°C	DM40 LiquiPhysics™ density meter	Metter Toledo, Switzerland	ASTM D 4052
Lower Heating Value	C2000 basic calorimeter-automatic	IKA, UK	ASTM D240
Reid Vapor Pressure at 37.8°C	Setavap 2 Automatic Vapour Pressure Tester	Paragon Scientific Ltd, UK	ASTM D5191
Oxygen content	CE440 Elemental Analyzer	Exeter Analytical, Inc., US	
Latent Heat of Vaporization	Differential Scanning Calorimetry	METTLER TOLEDO, UK	

Table 3. Properties of DAE and unleaded gasoline fuels

Properties	**Unit**	**Gasoline**	**DAE**
Formula		C_5–C_{12}	95%C_2H_5OH + 4.8%CH_3OH
Oxygen content	Wt.%	0	35.3
Density	Kg/m^3	736.8	795.7
Specific gravity		0.737	0.796
Lower Heating Value	MJ/Kg	44.03	28.42
Research Octane Number		97	108
Reid Vapor Pressure (at 37.8°C)	kPa	63.9	19.7
Latent heat of vaporization	kJ/kg	349	930

2.3. Experimental Procedure

The engine test conditions were controlled through CADET 10 software. The speed range of the engine was set from 1000 rpm to 4000 rpm at steps of 500 rpm. For each rotational speed, the settling time was set at 4 minutes and the idling time at 5 minutes. The throttle opening position was fixed at 50% throughout the experiment. There was no change in the compression ratio from the original manufacturer's value as no modifications were made. Meanwhile, the dynamometer mode has been set to speed as it will control the speed of the engine during the experiment.

The engine was first operated on gasoline for 15 min to stabilize the operating condition. The fuel was then changed to the alcohol blend. After sufficient amounts (approximately 1 Litter) of the blend were consumed, data were acquired to ensure the removal of residual gasoline from the fuel line. Each test engine was again operated under gasoline to drain all of the blends in the fuel line. To avoid system error and dispersion of the data, each experiment was run three times and an averaged value was used for the entire experiment.

3. Results and discussion

3.1. Engine performance

3.1.3. Torque and Brake power

Fig. 2 compares the engine torque given the test fuels. It is seen from figure that fuels with DAE reach peak torque slightly earlier than gasoline. On average, DAE10, DAE20, DAE30 and DAE50 increased the torque than gasoline by 1.2%, 1.7%, 3.5% and 4.2% respectively. As an oxygenated fuel, alcohols produce a lean mixture that makes burning more efficient [23, 24] and produce a higher torque than gasoline. The increased torque may also be attributed to the high latent heat of vaporization (HoV). Fuel vaporizes in the intake manifold and in the combustion chamber. When the Latent heat of vaporization of alcohol increases, charge temperature is lowered as the alcohol evaporates. Furthermore, charge density increases. Engine torque is also enhanced by associated fuel mass at the same air–fuel ratio. This result is consistent with those obtained by other researchers[4]. Under the experimental operating conditions, the maximum torque was 121.4 Nm at 4000 rpm which was achieved when using DAE50.

Fig. 3 shows, the brake power developed by all fuel blends for different engine speeds. The DAE gasoline blend produced a higher brake power than gasoline. As explained earlier, the higher flame velocity of DAE is probably the main reason for the differences observed at higher engine speeds. The improvements in torque and power at high engine speeds by hydrous ethanol are also revealed by other authors [14, 25]. At low engine speeds there is no significant change in brake power with respect to fuel change. Under half throttle engine conditions, the maximum brake power was found at 4000 rpm

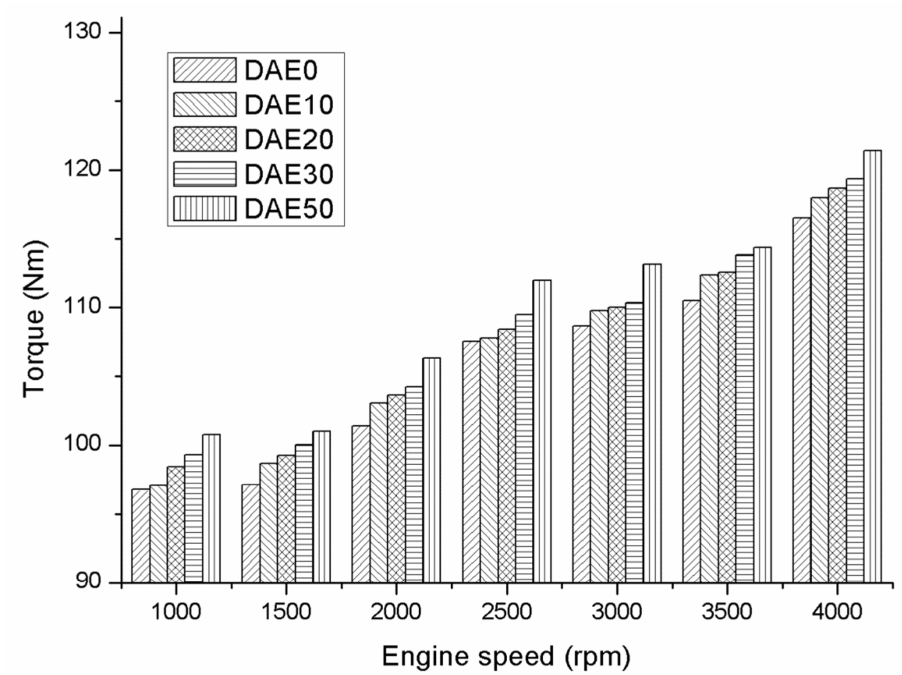

Fig. 2. The effect of DAE addition on torque

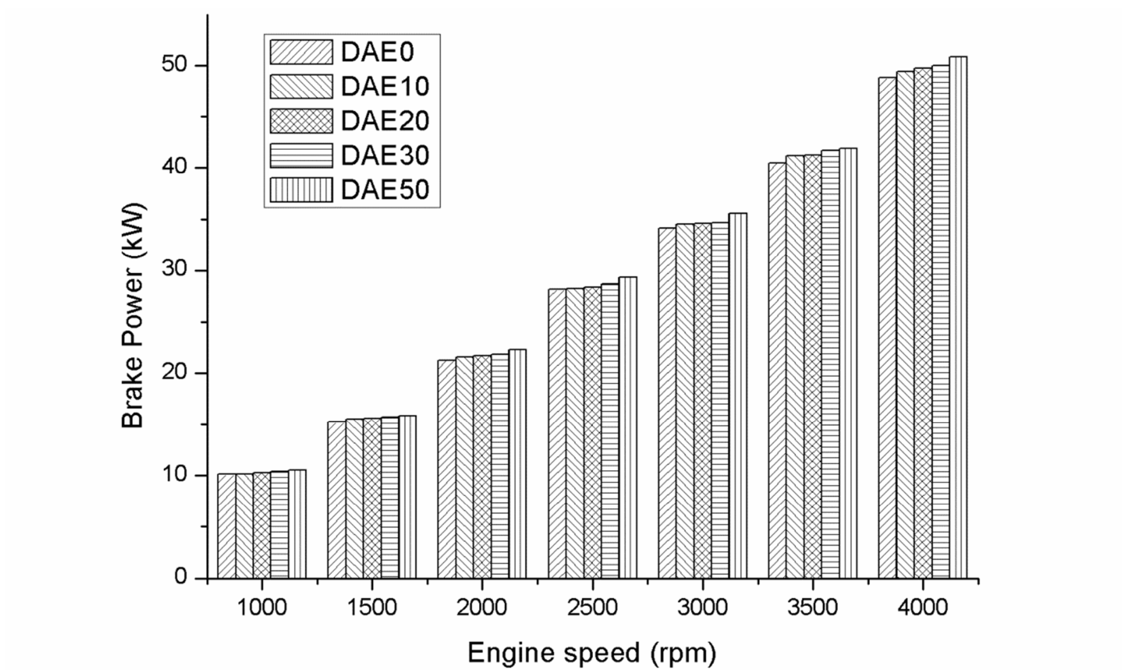

Fig. 3. The effect of DAE addition on brake power

3.1.1. Brake Specific Fuel Consumption

DAE addition to unleaded gasoline shows negative results in terms of fuel consumption. Fig. 4 shows the brake specific fuel consumption (BSFC) variation for various DAE-gasoline blends including base gasoline at different engine speeds. The BSFC for the entire power range are comparatively higher for all DAE-gasoline blends, than that of the base gasoline. On average, the BSFC values of , DAE10, DAE20, DAE30 and DAE50 were higher than that of unleaded gasoline by 2.7%, 5.3%, 8.1% and 14.3% respectively. This is because of the lower heating value of DAE compared to gasoline (Table 2) [26]. Therefore, more fuel is required to produce the same level of engine power for low LHV fuel. Higher density of DAE may also be another reason of higher BSFC for DAE-gasoline blend.[27] In all test fuels, BSFC decreased with engine acceleration because the volumetric and combustion efficiencies increased.

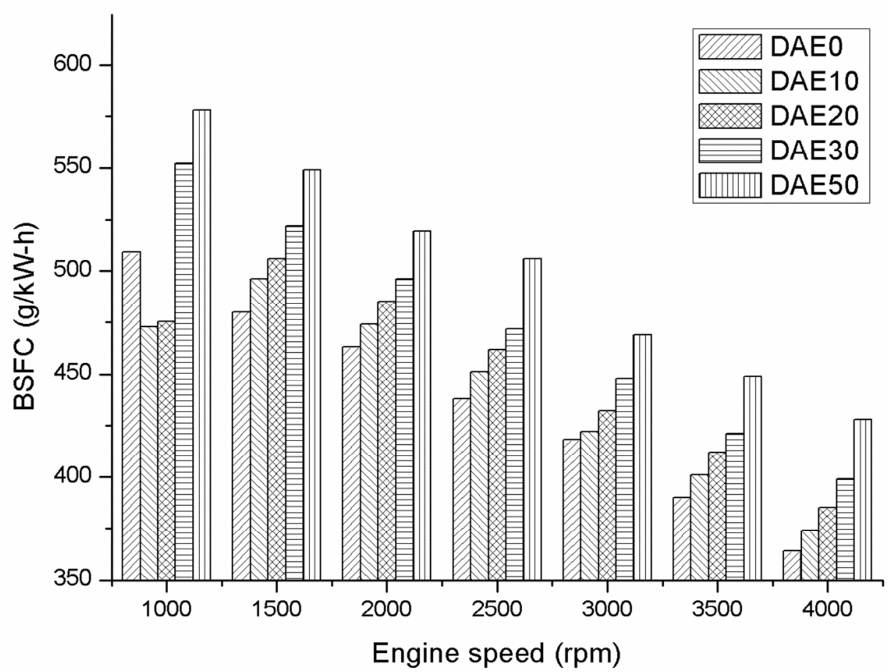

Fig. 4. The effect of DAE addition on brake specific fuel consumption

3.1.2. Volumetric efficiency

The engine torque and power mainly depend on the engine in-cylinder mixture mass. Therefore volumetric efficiency plays an important role, along with other engine parameters[28]. The effect of the DAE percentage in the blend on the volumetric efficiency of the engine is shown in Fig. 5. Volumetric efficiency depends upon actual intake air quantity, which is governed by the operating temperature inside the engine cylinder. As the latent heat of vaporization is higher for DAE, a considerable cooling of the intake manifold and engine cylinder occurs, compared to gasoline operation. This results in better mixture density and more air induction with the blends, and consequently a higher volumetric efficiency is observed [28]. On the other hand, when the charge is injected, heat is absorbed from the hot engine parts and residual gases which reduce the in-cylinder temperature. However, the higher specific heat of ethanol [29] results in a higher heat capacity of the charge which results in a temperature drop then that of gasoline. Hence, volumetric efficiency is reduced. Ethanol also contributes to the increase in the vapor pressure of the air fuel mixture. While the Reid vapor pressure (RVP) of DEA is only 19.7 kPa, the RVP of gasoline is typically in the range 63.9 kPa. Adding DAE to gasoline causes an increase in the vapor pressure of the mixture as it combines with certain low molecular weight hydrocarbons to form azeotropes. Azeotropes have lower boiling points than the hydrocarbons from which they are made, resulting in an increase in vapor generation at lower temperatures[30, 31]. The volumetric efficiency for all blends along with gasoline is found to decrease with an increase in engine speed. This can be attributed to the increased operating temperature at high speeds, which reduces the air intake. An increase in the engine speed also reduces volumetric efficiency as a shorter duration is available for air intake. Thus a lower volumetric efficiency was observed at high engine speeds [32].

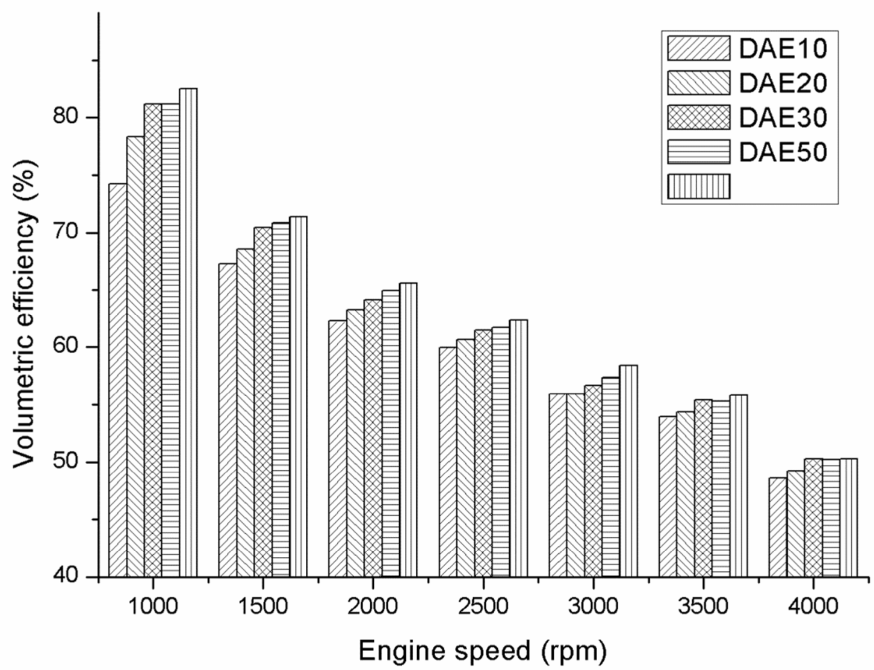

Fig 5. The effect of DAE addition on volumetric efficiency at half throttle

3.1.3. Brake thermal efficiency

Fig. 6 displays the BTE values of the different test fuels. On average, the thermal efficiencies of DAE10, DAE20, DAE30 and DAE50 were significantly higher than that of gasoline by 1.1%, 2.3%, 3.5% and 6.2% respectively. BTE is increasing with DEA portion increase on gasoline. This condition can be attributed to the fact that blends with higher DAE percentage contain more oxygen than those with lower DEA-gasoline blend. As a result, combustion is improved, thereby enhancing thermal efficiency.[33] Moreover, fuel is vaporized in the compression stroke when latent HoV is high. Given that fuel absorbs heat from the cylinder during vaporization, the air—fuel mixture is compressed more easily, thus improving thermal efficiency. Balki et al.[26] noted that the HoV and oxygen content of alcohol enhances BTE in alcohol—gasoline blends.

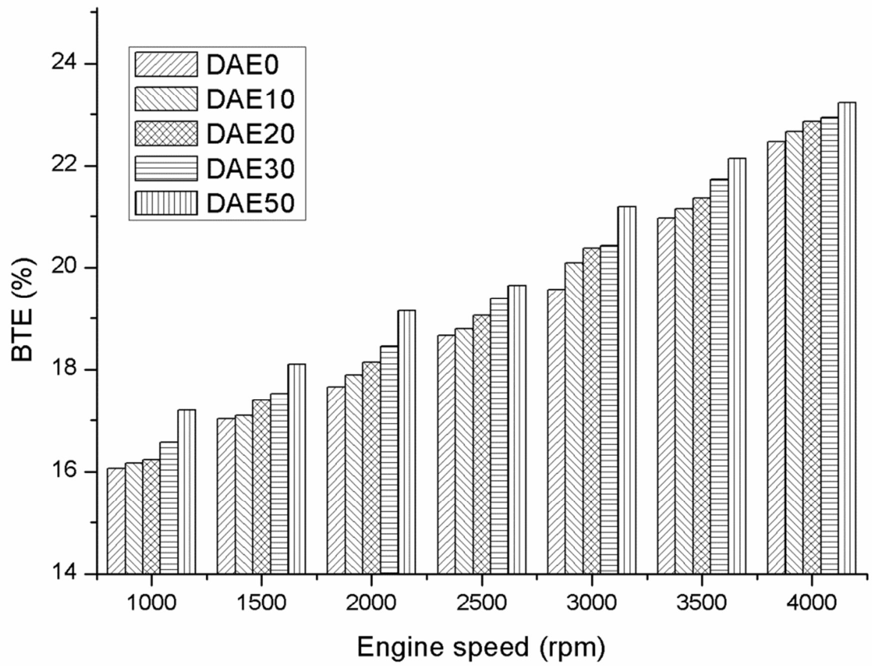

Fig. 6. Variation of BTE with engine speed.

3.2. Exhaust Emission

3.2.1. CO emission

CO emission represents a loss in the chemical energy that is not fully utilized in the engine. It is a product of incomplete combustion given either an insufficient amount of air in the air–fuel mixture or the interruption of combustion cycle time.[20] Fig. 7 depicts the variation in CO exhaust emissions in relation to engine speed. In, DAE10, DAE20, DAE30 and DAE50, CO emissions are significantly lower than those of gasoline by averages of 8.2%, 14.3%, 20.3% and 41.5%, respectively. Alcohols are oxygenated fuels; therefore, they enhance oxygen content in fuel for combustion. This process generates the "leaning effect", which sharply reduces CO emission.[34] Thus, alcohol—gasoline blended fuel emits less CO than gasoline fuel. This finding is consistent with that of previous studies, which utilized ethanol–gasoline blends.[35]

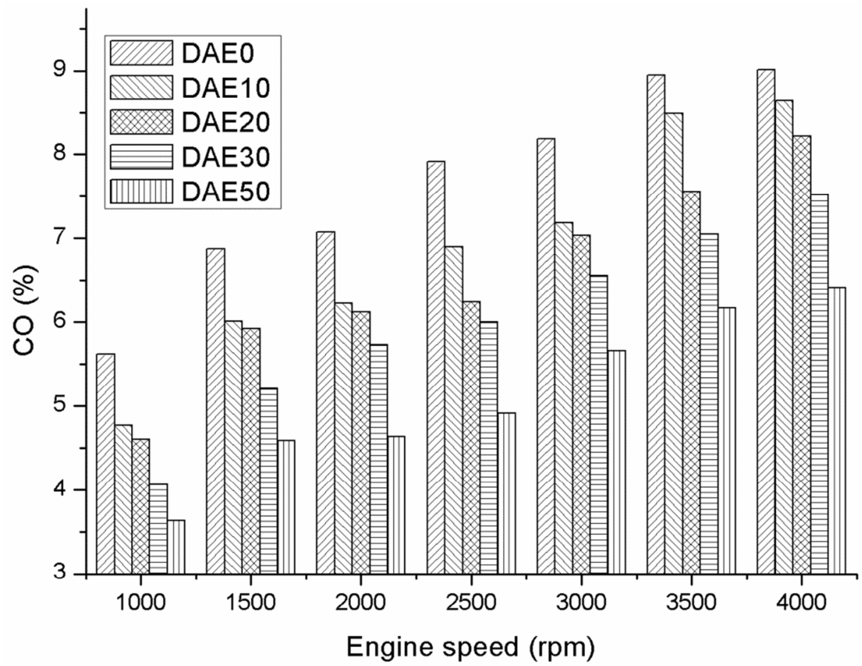

Fig. 7. The effect of DAE addition on CO emission at half throttle

3.2.2. HC emission

Emissions of unburned HC are primarily caused by unburned mixtures induced by improper mixing and incomplete combustion. These emissions are a main contributor to photochemical smog and ozone pollution.[36] Fig. 8 exhibits the emissions of unburned HC by all test fuels at speeds ranging from 1000 rpm to 4000 rpm. These emissions were slightly lower in all DAE—gasoline blends than in pure gasoline. On average, emissions of unburned HC by DAE10, DAE20, DAE30 and DAE50 significantly decreased by 1.6%, 3.0%, 4.7% and 7.6%, respectively. This result may be attributed to the leaning effect and the oxygen content in the DAE.[8] Moreover, these emissions decrease as engine speed increases in all blends. At high speeds, the air—fuel mixture homogenizes to increase in-cylinder temperature. This condition in turn enhances combustion efficiency. Thus, HC emission decreases more at high engine speeds than at low speeds. This conclusion is consistent with that of Koc et al.[8]

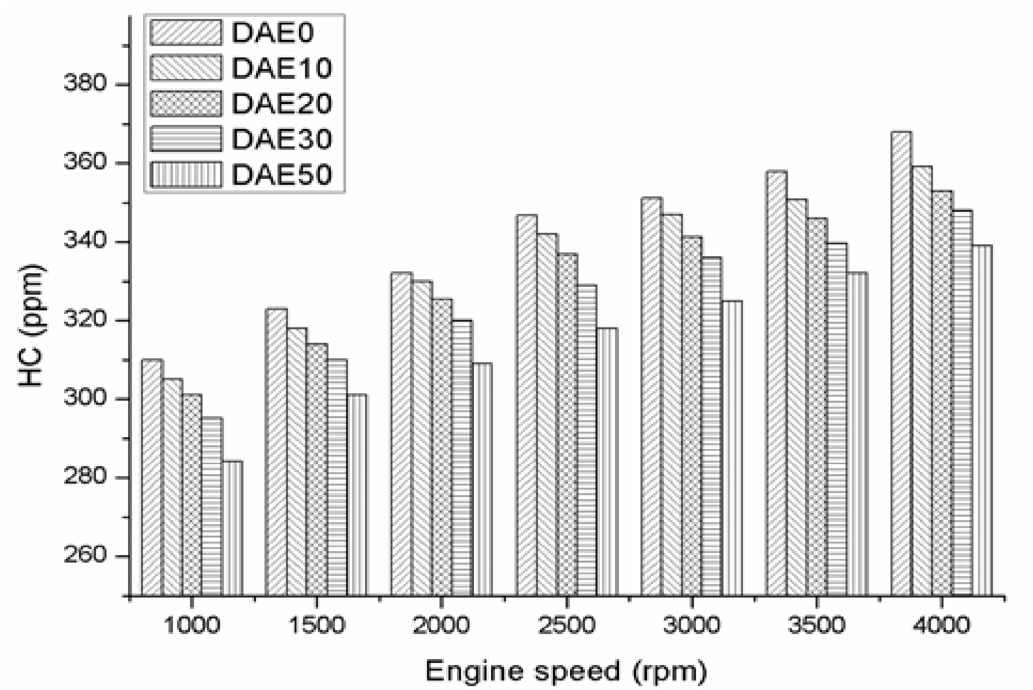

Fig 8 The effect of DAE addition on HC emission at half throttle

3.2.3. CO_2 emission

CO_2 is a GHG produced by the complete combustion of hydrocarbon fuel. Its formation is affected by the carbon–hydrogen ratio in fuel. Stoichiometrically, hydrocarbon fuel combustion should generate only CO_2 and water (H_2O). Fig. 9 presents the variation in CO_2 emission across different fuels. As per the study results, CO_2 emission is higher in alcohol–gasoline blends than in pure gasoline; on average, CO_2 emissions by DAE10, DAE20, DAE30 and DAE50 are 16.9%, 26.9%, 33.9% and 48.5% significantly higher than that of gasoline, respectively. This finding can be attributed to carbon flow rate. To attain a certain level of engine power given a constant throttle position, the amount of alcohol–gasoline blended fuel consumed must be higher than that of gasoline. Therefore, the carbon flow rates of the alcohol–gasoline blends are higher than those of gasoline.[37] The oxygen ratio in alcohols also enhances the combustion efficiency of alcohol–gasoline blends, which enhances CO_2 emission in alcohol—gasoline blends.

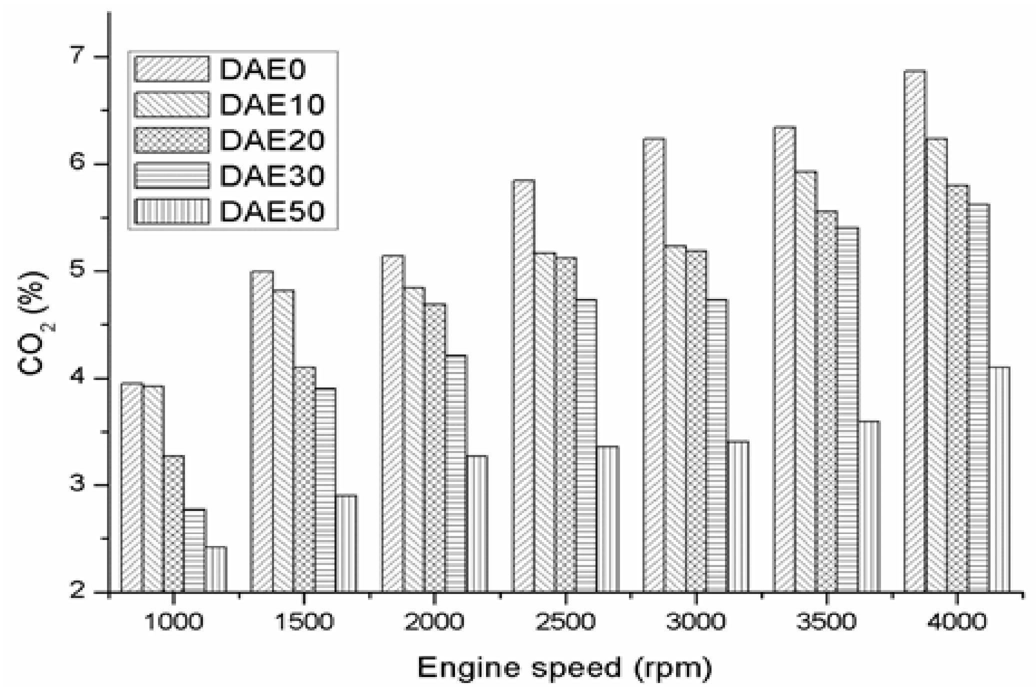

Fig. 9. The effect of DAE addition on CO_2 emission at half throttle

3.2.4. NO_X emission

During combustion at high temperature, nitrogen in the air oxidizes to form NOx. Thus, the generation of NOx in an engine is closely related to combustion temperature, oxygen concentration, and residence time inside the combustion chamber.[38] Fig. 10 exhibits the variation in NOx emission at different engine speeds. On average, NOx emissions by DAE10, DAE20, DAE30 and DAE50 are significantly lower than that by pure gasoline at 4.8%, 7.1%, 9.6% and 13.3%, respectively. This results may be ascribed to the lower LHV of the DAE—gasoline blend. Fuel with some water content reduce the peak in cylinder temperature emission [39]. Higher peak in-cylinder temperature is also a reason of high NOx emission [40]. As DAE contains 0.2% of water content, it also may be a reason if lower NOx emission for DAE-gasoline blend. DAE50 displayed the lowest NOx emission. Moreover, NOx emission increased with the acceleration of engine speed in all of the tested fuels. At high speeds, increased amounts of fuel are burned. Furthermore, torque and BSFC increase, and as a result, in-cylinder temperature increases. This increase may also enhance NOx emission instead of lowering heating value. [39]

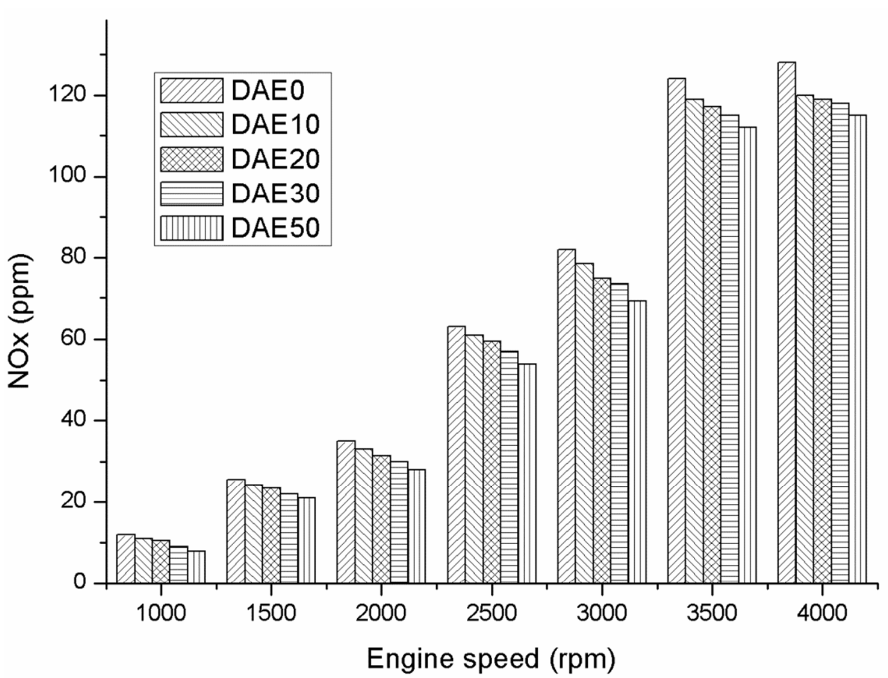

Fig. 10. The effect of DAE addition on NO_X emission at half throttle

4. Conclusion:

Experimental investigations of engine performance and exhaust emissions were carried out using a DAE-gasoline blend in a gasoline engine. From the experiment the following are found:

- DAE-gasoline blended fuels exhibited better engine torque, power, volumetric efficiency and BTE than that of gasoline. Higher oxygen content and faster flame speed of DAE may be the reason of better engine performance.
- As expected, DAE-gasoline blended fuels increase the BSCF than gasoline as like other lower LHV fuels.
- All DAE-gasoline blend emitted HC and CO emission lower than gasoline fuel. As like other oxygenated fuel, the oxygen content of DAE enhance combustion process and reduce CO and unburned HC emission. However, DAE-gasoline blends increase CO_2 emission.
- The NOx emission of DAE-gasoline blends was slightly lower than gasoline fuel. May be the water content of DAE and the lower heating value reduce the peak in cylinder temperature as well as NOx.

From the experiments conducted it is quite apparent that, like other alcohols DAE is a promising alternative fuel for SI engine.

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