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AN EXPERIMENTAL INVESTIGATION OF DENATURED ANHYDROUS ETHANOL-GASOLINE FUEL BLENDS ON THE PERFORMANCE AND EMISSION CHARACTERISTICS OF A SI 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. In Malaysia, commercial ethanol or denatured ethanol is available as 94.8% ethanol with 5% methanol and 0.2% water. Tests were carried out at half throttle and under variable speed conditions for a speed range of 1000 to 4500 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.It was observed that DAE has a significant positive effect on the performance of the gasoline engine. The results showed that blending of gasoline with DAE slightly increases the volumetric efficiency, brake power as well as torque with slide increase of BSFC. In addition, DAE15 shows better torque, volumetric efficiency and DAE20 shows higher BSFC than the other fuel blend. However, DAE also reduces CO emission with slide reduction of CO2 but slight increase of HC emission. Compering with other fuels, DAE10 shows lower CO and HC emission. In terms of investigated parameters, up to 20% blends with gasoline have been found as the promising fuel for the gasoline engines.*

Keywords: Denatured Anhydrous Ethanol (DAE), Gasoline engine, Performance, Emission

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]. Fossil fuels are "dirtier" source of power. While some fossil fuels do burn cleanly, most do not. Typical emissions from engines are carbon dioxide, soot, carbon monoxide, nitrogen oxides, sulfur dioxide, aldehydes and polycyclic aromatic hydrocarbons etc.

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 [4-6]. Research on the use of alternative fuels such as methanol and bio-ethanol and their blends in spark ignition engines is being intensively proposed because of their potential for low exhaust emissions [7-9]. A lower percentage of ethanol in ethanol-gasoline blends can be used in unmodified engines without serious problems. 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 [10].

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[11]. As a result of these properties, ethanol enhances the engine's performance and lowers emissions. Liu et al. [12] 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. [8] 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. 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. [13] 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.

Almost all the research previously concluded adopted either pure ethanol or pure methanol. So far few works have been done on denatured ethanol. Therefore this research focuses on an investigation into the effect of DAE-unleaded gasoline blended fuel on a SI engine in term of performance parameters and exhaust emissions.

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 (EC) dynamometer with a maximum braking power of 80kW and maximum speed of 9000 rpm.

Table 1. Engine technical data

Type	**1.6L multi cylinder engine**
Model	GA6D
No. of cylinders	4
Valve mechanism	16-Valve DOHC
Total displacement	1594cc
Bore	78mm
Stroke	83.4mm
Combustion chamber	Bowl
Max Power	79.4278kW @ 5700rpm
Max torque	143.42 Nm @ 4500rpm
Fuel system	Multiple port injection

The fuel metering system uses gravimetric analysis to measure the fuel consumed by the engine. The fuel is weighed in a measuring vessel whilst being supplied to the engine. A capacitive sensor detects the change in mass inside the vessel. The voltage generated by the capacitor will then be interpreted by the CADET10 software as the fuel is consumed by the engine. Furthermore, the air flow into the engine is measured by an air flow meter. 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 (NDIR) to determine CO, CO_2 and HC concentrations.

2.2. Fuel selection

DAE and unleaded gasoline (U97 from a Shell gas station) 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 [14]. 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 [15]. DAE consists of ethanol (purity of 99.7%) of about 94.8% by volume, methanol of about 5% by volume and the rest is water. Table 2 presents a comparison between the physicochemical properties of gasoline and DAE.

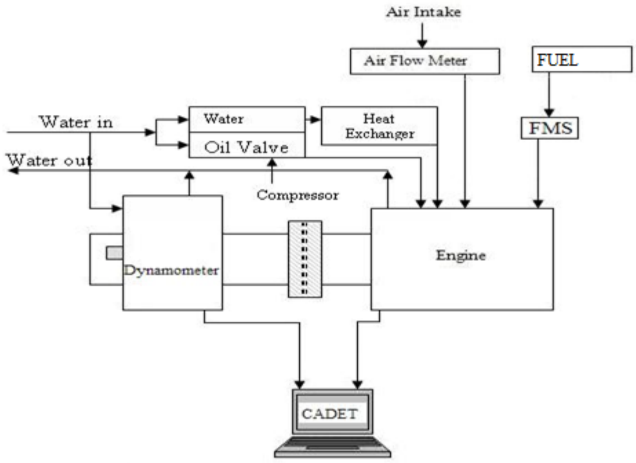

Fig. 1. Schematic diagram of the engine test bed

Table 2. Properties of DAE and unleaded gasoline fuels

	Unleaded gasoline	**Denatured anhydrous ethanol**
Formula	C_7H_{17}	95%C_2H_5OH + 4.8%CH_3OH
O(%mass)	0	35.3
Density (Kg/m^3)	737.5	795.7
Net heating value (MJ/Kg)	44.03	30.29
Research octane number (RON)	97	--
Specific gravity	0.7375	0.795

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 4500 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.

Before every fuel change, the fuel tank and lines were cleaned. Before taking readings with the new fuel the engine was allowed to run at 1000 rpm and in 50% throttle position for some time to remove any remaining fuel from the previous experiment. Then the readings were taken.

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. For this experiment, the engine rotational speed (rpm), torque, brake power, fuel mass flow, air mass flow and CO, CO_2 and HC emissions were measured.

3. RESULTS AND DISCUSSION

3.1. Engine performance

3.1.1. Air and fuel mass flow

It appears from Fig. 2 that for any DAE-unleaded gasoline fuel blend, the λ valueincreases with decreasing speed where λ is the air fuel equivalence ratio. The λ value is dominated by the actual air-fuel ratio as well as by air mass flow. As the engine speed decreases, the air fuel ratio increases because a longer time is available for air intake than at higher speeds [16].

In most cases, the λ value is higher for DAE gasoline blends than pure gasoline. The increase in λ value liaises with the increase in DAE percentage in the fuel blend, as DAE is an oxygenated fuel. The lower stoichiometric air fuel ratio of DAE is also a reason for higher λvalues for DAE addition with gasoline.

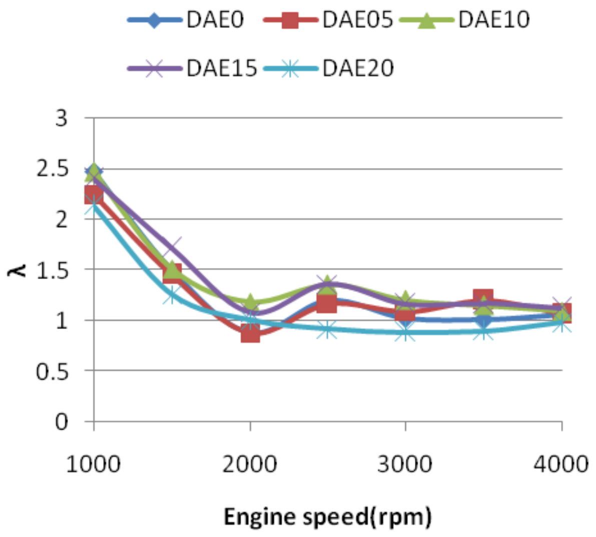

Fig. 2. The effect of DAE addition on λ values at half throttle

3.1.2. Brake Specific Fuel Consumption

DAE addition to unleaded gasoline shows negative results in terms of fuel consumption. Fig. 3 shows the 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 blends, than that of the base gasoline. This is because of the lower heating value of DAE compared to unleaded gasoline (Table 2). Fig. 3 also depicts the varying relationship between BSFC values and the change in DAE concentration of the blends. This is due to the diversity in the nature and compositions of the blends. When only ethanol is used with unleaded gasoline, the BSFC increases with the increase in ethanol in the blends [17]. But the addition of methanol intervenes in the stability, water tolerance and phase separation of the fuel which in turn affects the fuel metering and atomization characteristics resulting in erratic engine operation [18, 19]. Fig. 3 also shows that with increasing engine speed the BSFC increases for all fuels as more fuel is required for high-speed operation.

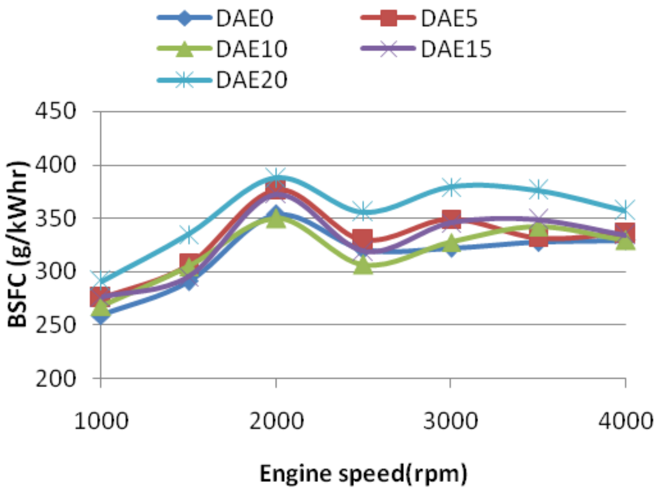

Fig. 3. The effect of DAE addition on brake specific fuel consumption at half throttle

3.1.3. 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 [20]. The effect of the DAE percentage in the blend on the volumetric efficiency of the engine is shown in Fig. 4. 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 [20]. 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 [21] 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 ethanol is only 4.6 psi (32 kPa), the RVP of gasoline is typically in the range 7-9 psi (48-63 kPa). Adding ethanol 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 [22, 23]. The combined effects of these three phenomenon results in a zigzag pattern in the volumetric efficiency curve for different blends. However, in most cases volumetric efficiency is found to increase with an increase in the DAE ratio of the blend. The same phenomenon was found in previous studies on alcohol [18, 24].

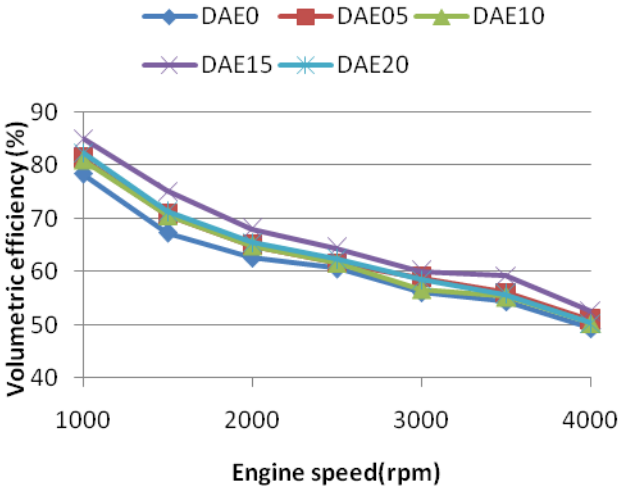

Fig. 4. The effect of DAE addition on volumetric efficiency at half throttle

3.1.4. Torque, BMEP and Brake power

Alcohol fuels usually reach peak torque and BMEP lightly earlier than gasoline. BMEP is directly proportional to torque [25]. Fig. 7 shows a slightly higher increase in torque and BMEP at higher speeds when DAE-gasoline blends were used as the fuel. As an oxygenated fuel, alcohols produce a lean mixture that makes burning more efficient[18, 26] and produce a higher torque than gasoline.At higher engine speeds there is less time available to complete the combustion in an engine cycle. In this condition, a faster flame velocity plays an important role in completing the combustion, which in turn enables DAE to produce a higher torque and BMEP than gasoline. At lower engine speeds, the opposite situation occurs, which can be attributed to the higher heating value of gasoline (Table 1). Under the experimental operating conditions, the maximum torque was 121.4 Nm at 1500 rpm which was achieved when using DAE50, and the maximum brake power is 42 KW at 4000rpm when the DAE50 blended fuel was used.

Fig. 8 shows, the brake power developed by all fuel blends for different engine speeds. The DAE gasoline blend produced a higher brake power than gasoline at higher speeds (up to 4000rpm). 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 [25, 27]. 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.

3.2. Exhaust Emission

3.2.1. CO emission

The variation in CO emission with respect to engine speed and fuel are observed in Fig. 7. It is seen from Fig. 7 that CO emissions are lower for the DEA-gasoline blend than gasoline. This may be due to higher oxygen content of the DAE molecules, which favors the conversion of the CO into CO_2 by better combustion [25, 28, 29]. Under the experimental conditions, DAE40 shows lower CO emission than other fuel blends.

Fig. 7 also shows that CO emission increases with engine speed in most cases. As the rpm increases, the air-fuel mixture gets a shorter time to complete combustion, which results in greater CO emission. At 2500 rpm, CO emission dropped for all blends. This may because of a higher λ value at 2500 rpm, which makes the mixture leaner and results in complete combustion.

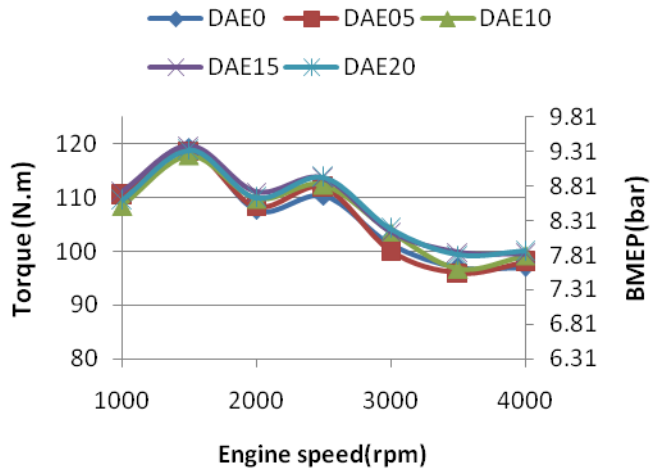

Fig. 5. The effect of DAE addition on torque and BMEP at half throttle

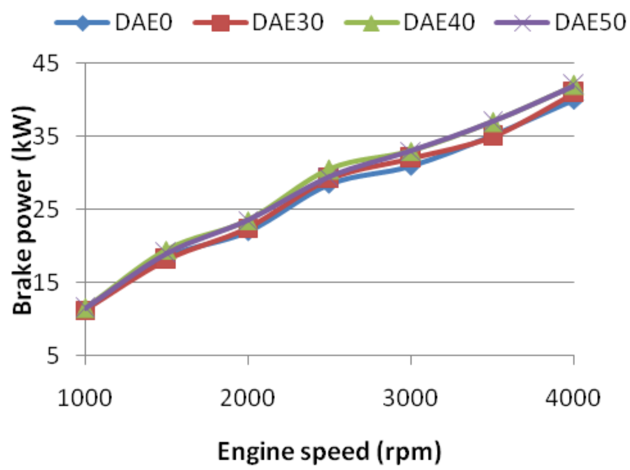

Fig. 6. The effect of DAE addition on brake power at half throttle

3.2.2. HC emission

As demonstrated in Fig. 8, HC emission increase as the engine speed increases. This may be because the air-fuel mixture gets a shorter time to complete combustion at higher engine speeds. However, at 2500rpm the HC emission dropped for all blends. This may be because of the higher λ value, which makes the mixture leaner and leads to complete combustion. For different blends, HC first increases with the augmentation of the DAE percentage and then decreases. The increase in HC can be attributed to the advanced combustion process for the faster flame velocity of DAE, which weakens the post oxidation of HC. However, as the DAE concentration increases, the amount of DAE in the blend increases. As DAE does not have heavier hydrocarbons, it induces complete combustion and this may be the reason for the lower HC emission in higher DAE blends. DAE40 results in a lower HC emission than the other blends. The HC emission curves also follow the inverse trend of the λ value curve.

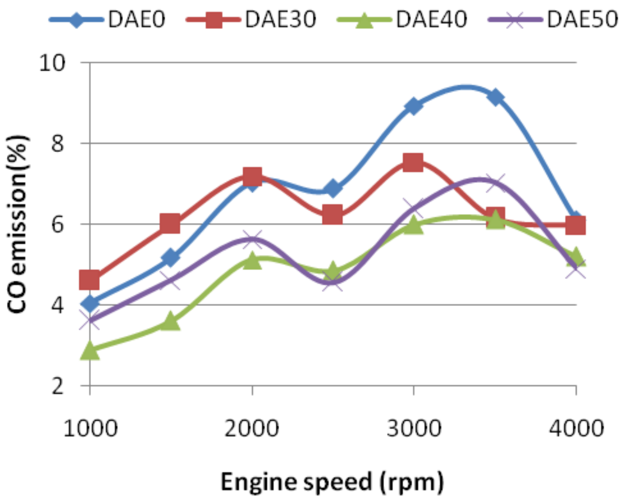

Fig. 7. The effect of DAE addition on CO emission at half throttle

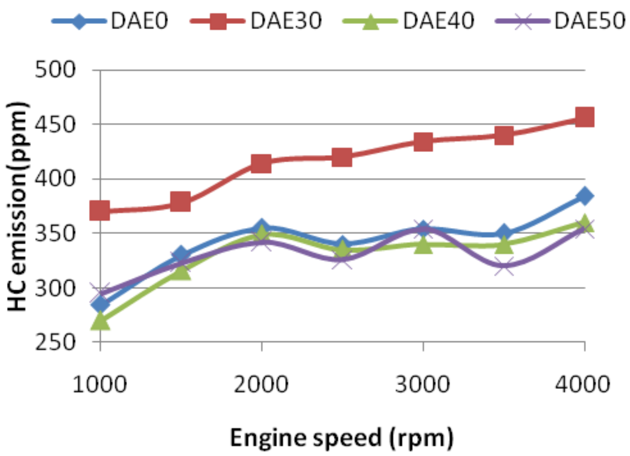

Fig. 8. The effect of DAE addition on HC emission at half throttle

3.2.3. CO2 emission

Fig. 9 shows the CO_2 variation for various DAE-gasoline blends including base gasoline at different speeds. CO_2 emission exhibited the opposite behavior to the CO emission and CO_2 emission graphs which followed the λ value curve. This can be attributed to its lower volumetric efficiency (shown in Fig. 4). However, in most cases it was observed that, with the addition of DAE to gasoline CO_2 emission reduced, except for the DAE50 blend. For the better combustion characteristics of an oxygenated fuel, CO_2 emission decreased with DAE addition.

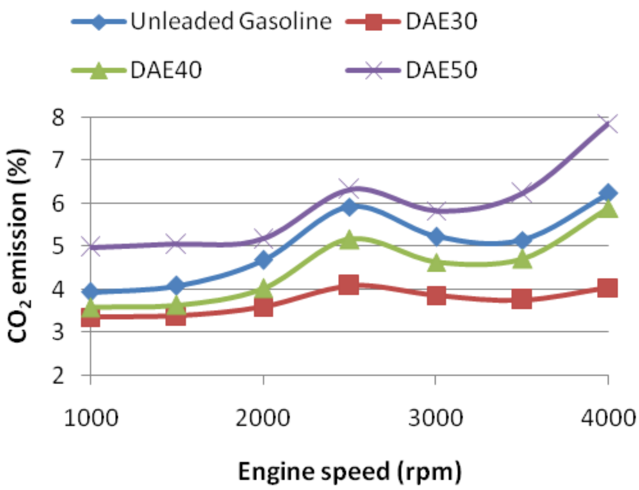

Fig. 9. The effect of DAE addition on CO_2 emission at half throttle

4. CONCLUSION

Experimental investigations were carried out using a DAE-gasoline blend in a gasoline engine. It was seen that when the engine was fuelled with DAE gasoline fuel blends the BSFC was higher as lower heating values of alcohols. However, the addition of DAE in gasoline improves the engine performance parameters, such as torque, BP and volumetric efficiency. Especially at higher engine speeds, DAE helps improve engine performance due to its faster flame velocity. The additional cooling effect of DAE due to high latent heat of evaporation increases volumetric efficiency. Among all blends DAE40 shows better engine performance.

This study also investigated the CO, HC and CO_2 emissions for DAE-gasoline blended fuels. The CO emission was reduced with DAE addition due to its higher oxygen content. In the case of HC emissions, DAE addition does not produce a satisfactory result. CO_2 emission was reduced with DAE due to the lower carbon mass flow of the DAE gasoline blend. DAE40 presents lower emission among all fuels tested for overall engine conditions. Thus it can be concluded that it, like other alcohols, it is a promising alternative fuel for SI engine.

5. ACKNOWLEDGMENT

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