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Optimization of Fuels Containing C_2-C_6 Alcohols and Gasoline and Their Effect on Engine Performance

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Abstract. Alcohols with higher carbon number (C_3 to C_6) have the potential to use as an alternative, as they offer higher energy content, octane number and petroleum displacement. This study focusses on improvement of different physicochemical properties using multiple alcohols (C_2 to C_6) at different ratios compared to that of the ethanol-gasoline blend (E10/E15). To optimize the properties of multiple alcohol-gasoline blends, properties of each fuel were measured. Optimization tool of Microsoft Excel, "Solver" was used to find out the optimum blend. Three optimum blends with maximum heating value (MaxH), maximum research octane number (MaxR) and maximum petroleum displacement (MaxD) are selected for testing in a four cylinder gasoline engine. Optimized blends produce higher BTE and lower BSFC than that of E15 fuel. Thus, optimized multi alcohol-gasoline blends were found to be a better option in terms of fuel properties and engine performance for a gasoline engine.

Keywords: Ethanol; Alcohol, Optimization, Performance, Gasoline engine.

1. Introduction

The replacement of petroleum gasoline with alternative fuels is an important issue among all energy based researchers and manufacturers. Increasing petroleum fuel price, threats to the environment from engine exhaust emissions, depletion of fossil fuels, global warming effects and energy concerns have generated more interest in alternative sources of fuel [1]. However, global energy consumption has increased sharply in recent decades. According to the IEA, global energy consumption will increase by about 53% by 2030 [2]. The United States EIA has projected that the world's liquid fuel consumption will increase from 86.1 million barrels/day, to 110.6 million barrels/day by 2035 [3].

There is a growing interest in using alcohols as an option to substitute petrol in spark ignition engines and extensive research has been carried out. The use of alcohols involves oxygen enrichment, octane enhancer, reduce carbon monoxide emission etc. Among all alcohols, ethanol is the most researched alcohol to be used as alternative fuels. In many countries, government mandate to use ethanol with gasoline. Environmental Protection agency (EPA) issued a waiver to authorize up to 15% of ethanol blended with gasoline to be sold only for cars and light pickup trucks with a model year of 2001 or newer [4]. The US Renewable Fuel Standard (RFS2) mandates in the production of ethanol and advanced bio-fuels up to 36 billion gallons in 2022 [5]. Higher carbon number alcohol can be a better alternative to fulfill the huge demand of ethanol. In other hand, LHV is the main difficulty prevents of ethanol the use as fuel for gasoline engines. More fuel required to achieve the same power if lower LHV fuel is used [6]. However, it is seen in the literature that the carbon number of alcohol increases, the LHV increases. Mixing ethanol with higher carbon number alcohols (propanol, butanol, pentanol, hexanol) may solve the problem of lower LHV of ethanol. On the other hand all of these alcohols can be produced from coal-derived syngas that is a renewable source [7]. Moreover, the concept of biorefinery for higher-alcohol production is to integrate ethanol formation via fermentation with the conversion of this simple alcohol intermediate into higher carbon

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number alcohols [8]. The advantages of a higher octane number of ethanol may be properly utilized by blending with higher carbon number alcohol as high carbon number alcohol having a low octane number. Thus, multi-alcohol gasoline may provide better results in fuel property as well as engine output. Some authors have optimized fuel properties using blends of multiple alcohols with gasoline and got better fuel properties than conventional ethanol gasoline blend [9, 10].

However, no research has been done considering fuel properties of the multi alcohol gasoline blend. However, there is a lack of research on optimization of fuel properties of multiple alcohol-gasoline blend and their effect on engine performance. The objective of this research is to find optimized blends of ethanol, propanol, butanol, pentanol, hexanol and gasoline blend as alternative of E10/E15 blend and analyze the effect of optimized blends on engine performance with respect to E15 and gasoline.

2. Materials and Method

2.1. Fuel selection

Ethanol, propanol, butanol, pentanol and hexanol were chosen for this study. Branched isomers of propanol, butanol and pentanol were used as they have higher octane numbers. However, straight (n-) isomer for hexanol was used due to its low cost compared to iso-hexanol.

2.2. Properties prediction method

Physiochemical properties related to engine operation for alcohol-gasoline blends must be predicted in order to identify an optimum blend. Density, LHV, heat of vaporization (HoV), RON, RVP etc. are the most crucial properties when evaluating a fuel for customer satisfaction, engine requirements, meeting legislative requirements, and maintaining industry standards. Thus to compare fuels with volumetric amounts of different alcohols, these fuel properties were selected and compared to E15.

Some of these properties, including density, LHV, HoV, and oxygen content, are obtained with straightforward calculations if basic assumptions are made about the mixture. These calculations remain straightforward regardless of the number of components in the blend because they are linear combinations of the properties of the blend components. Other properties, like the distillation profile, RON, and RVP, are significantly more complicated to calculate. The process to calculate each of the non-linear properties is detailed here.

Density, LHV, HoV, and oxygen content have a linear relationship of the properties of the blend components. Equation 1 is used to predict the density, LHV, HoV and oxygen content of blends.

$$property_{blend} = \sum_{i=1}^{n} v_i \times property_i \tag{1}$$

The addition of alcohol with gasoline results in a nonlinear change in octane number when considered on a volumetric basis [11]. Anderson et al. [12] found that the molar alcohol concentration may be more appropriate than volumetric concentration to describe the dependence of RON and MON on alcohol content. They simplify the calculation of RON by based on the molar fraction of alcohol in a blend, where x_{alc} is the molar fraction of alcohol in blend in equation 2.

$$ON_{blend} = (1 - x_{alc})ON_{base} + (x_{alc})ON_{alc} \tag{2}$$

Estimation of vapor pressure of ethanol-gasoline blend is complicated because they form complex non-ideal solution. Reddy [12] developed a model using the UNIFAC method to predict vapor pressure of ethanol-gasoline blend, which was used in this study. For the higher carbon number alcohols (C3-C6), curves were drawn using experimental data and extrapolated in alcohol-gasoline blend to predict blend RVP.

The optimization of blend properties was done by using Excel solver tools in Microsoft excel. This optimizer allows linear, non-linear and integer programs to be solved within the spreadsheet. In the spreadsheet, fuel volume concentrations were designated as decision variable, volume concentration was changed to obtain desired properties. Required equations to predict properties were put in excel solver tools and target values will be explained in the next chapter. From all optimized combination three best combinations were chosen for maximum heating value, maximum RON number and maximum petroleum displacement.

2.3. Target properties for optimum blends

To evaluate its prospect as a fuel, a substance must meet the desired properties first. The objective of the E10/E15 Alternate scenario is to identify multi-component blends that could be used in current engines and offer higher petroleum displacement, knock resistance, and/or energy content than E10/E15 while adhering to industry standards and consumer expectations. These blends have oxygen content that meets the EPA E15 waiver, knock resistance of E10 or better, vapor pressure within ASTM standards, minimum energy content equal to that of E15, and petroleum displacement at least equal to that of E15. These criteria and their values are summarized in Table 1.

3. Experimental Set Up

The tests were carried out in the Engine Laboratory of Mechanical Engineering Department, University of Malaya on a four-cylinder gasoline engine. The detail of the engine is described in Table 2. The test engine coupled to an eddy current dynamometer (Froude Hofmann model AG150), with a maximum power 150kW. To carry out tests using alcohol blends in this engine, it was first run with gasoline for a few minutes to get a steady operating condition. Then fuel was changed to alcohol blend. After consumption of sufficient blend, the data acquisition was started to ensure the removal of residual gasoline in the fuel line. After each test engine was again run with gasoline to drain out all the blends in the fuel line. This procedure was followed for all the blends. The engine was operated between 1000 rpm to 6000 rpm with a step of 1000 rpm at 100% load condition. Fuel flow was measured using KOBOLD ZOD positive-displacement type flow meter. CADET 10 Data Acquisition System collects the data automatically. All the measurements were triplicated and the performance measurements during each test were highly repeatable within that test series.

Table 1: Target value of optimum

Properties	**Unit**	**Alternative fuel's target**
LHV	MJ/kg	≥41.65
RON	--	≥96.24
RVP	kPa	34 to 62
Oxygen content	wt%	≤5.205
Petroleum displacement	vol%	≥15%

Table 2: Specification of the tested engine

Engine parameter	**Value**
Number of cylinder	4
Displacement volume	1596 cm^3
Bore	78mm
Stroke	84mm
Connecting rod length	131mm
Compression ratio	10mm
Max output (/rpm)	78kW/6000
Max torque (/rpm)	135N-m/4000

4. Result and Discussion

4.1. Optimum blend properties

Three optimum blends selected with maximum LHV, maximum RON and maximum petroleum displacement are denoted as MaxH, MaxR and MaxD respectively. All three blends met targeted fuel properties for alternative fuel that described in table 1. All these suitable blends are represented in fig. 1 and properties of these blends are shown in Table 3.

Table 3: Properties of optimum fuels and improvement over target

	Expected value	MaxR	MaxH	Max PD
RON	≥96.24	**100.71 (+4.65%)**	96.24 (0%)	96.58 (+0.35%)
LHV	≥41.65	41.77 (+.29%)	**42.45 (+1.92)**	41.8 (+0.36)
Petroleum displacement	≥15	19.57 (30.47%)	15.28 (+1.8)	**19.85 (+32.27)**

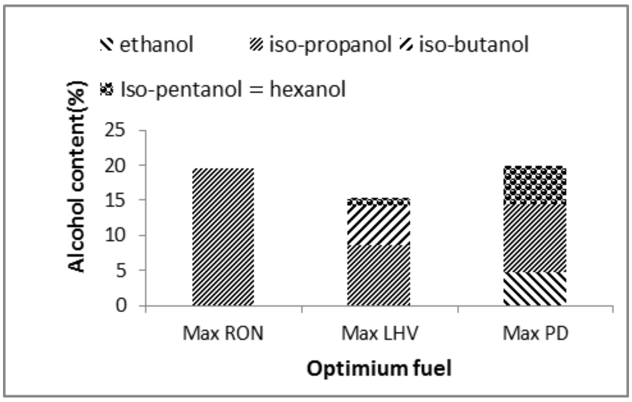

Fig. 1: Composition of the optimum fuels

4.2. Torque

Torque curves at full throttle, considering gasoline and other alcohol-gasoline blends, are plotted in fig. 2. The engine speed ranging from 1000 to 6000rpm is charted on the horizontal axis. It can be seen that, torque for all alcohol-gasoline blends are slightly higher than that of gasoline fuel. Among all alcohol gasoline blend, E15 shows the highest torque, though it has lowest LHV than that of other blends. The maximum brake torque is available in 4000 rpm engine speed and those were 129.3Nm, 131.5 Nm, 129.52 Nm, 130.9 Nm and 131.5 Nm for gasoline, MaxR, MaxD, MaxH and E15 blend respectively. This result may be explained using latent heat of vaporization. The vaporization of the blend can occur in the intake manifold or in the combustion chamber. The evaporation in intake manifold increases the charge density and associated fuel mass for the same air fuel ratio which in turn results in more torque. A similar result is obtained by other researchers [13, 14]. The addition of oxygenated alcohol produces a lean mixture that makes the burning more efficient than gasoline, which can be added as another reason [15]. The improved anti knock behavior of alcohol-gasoline blend allowed a more advanced timing that results in higher torque [16].

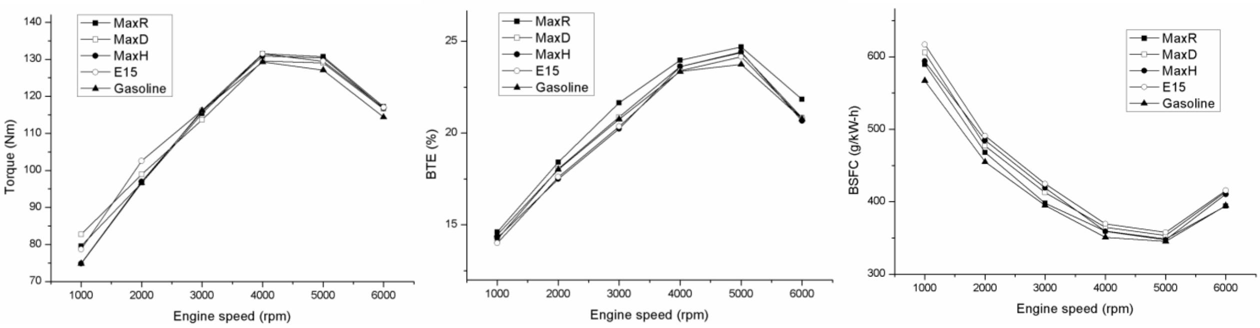

Fig. 2. Engine performance parameter for varying engine speed

4.3. Brake specific fuel consumption

Fig. 2 illustrates the brake specific fuel consumption at WOT for all tested fuels. It can be seen that gasoline shows the lowest BSFC compared to other alcohol gasoline blends with the entire engine speed. Higher LHV of gasoline is the probable cause of lower BSFC of gasoline. It was attained that the value of minimum BSFC with gasoline is 345.3 g/kW h. However, average BSFC were increased 6.7%, 2%, 4.76% and 4.26% for E15, MaxR, MaxD and MaxH blend compared to gasoline. The lower energy content of fuel causes some increment in BSFC of the engine when it is used without any modification [17]. Higher density of alcohols might be another reason of higher BSFC of alcohol [15]. Usage of optimized blends instead of E15 shows some improvement here. With displacing more than 15% gasoline, optimized blends were showed lower BSFC than that of E15. This is because of better fuel properties (e.g. LHV in case of BSFC) of optimized blend. This produced same brake power with lower fuel consumption than that of E15.

4.4. Brake thermal efficiency

Thermal efficiency indicates the ability of the combustion system to accept the experimental fuel, and provides comparable means of assessing how efficient the energy in the fuel was converted to mechanical output [18]. Fig. 2 presents the effect of using alcohol–gasoline blends on brake thermal efficiency with respect to engine speed. Brake thermal efficiency increased with engine speed until 5000 rpm and maximum thermal efficiency was approximately 24.69%, 24.38%, 24.42%, 24.16% and 23.74% when MaxR, MaxD, MaxH, E15 and gasoline were used as fuel respectively. In general, the addition of alcohol led to an increase of BTE. The combined effect of LHV, HoV and RON plays an important role in thermal efficiency. The increased ignition delay results in a slower energy release rate, which reduces the heat loss from the engine because there is not enough time for this heat to leave the cylinder through heat transfer to the coolant [7]. M.K. Balki et al. [17] explained, heat of vaporization and oxygen content of alcohol as the reason of higher BTE for alcohol gasoline blends.

5. Conclusion

The main objective of this study was to improve the energy content, knock resistance, and/or petroleum displacement using multi alcohol-gasoline blend compared to traditional ethanol blends such as E10/E15 while maintaining specified fuel properties. The performance characteristics were measured for those multi-alcohol gasoline blends and compared with gasoline and E15 blend. Based on experimental observation the following conclusion can be made:

- Among all multi alcohol-gasoline fuel combination three optimum blends were selected on the basis of maximum LHV, maximum RON and maximum petroleum displacement and these optimized fuels improved LHV, RON and displacement by 1.92%, 4.65% and 32.27% respectively.
- Optimized blends improved engine torque and BTE than gasoline and E15. MaxR blend showed highest BTE than other blends and the improvement of BTE was 3.36% than that of gasoline.
- BSFC were higher for optimized blends than gasoline. However, MaxR, MaxD and MaxH blends reduced BSFC 4.39%, 1.8% and 2.27% respectively than that of E15 fuel.
- The overall results showed that optimized blends have improved fuel properties and shows better performance in gasoline engine without any modification. Thus optimized blends can be used with better engine performance than that of E15 fuel with more petroleum fuel displacement.
- Further research is required to study the feasibility of commercial use of multi alcohol-gasoline fuels in SI engine.

6. Acknowledgment

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