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Tailoring the key fuel properties using different alcohols (C_2–C_6) and their evaluation in gasoline engine

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ABSTRACT

The use of ethanol as a fuel for internal combustion engines has been given much attention mostly because of its possible environmental and long-term economical advantages over fossil fuel. Higher carbon number alcohols, such as propanol, butanol, pentanol and hexanol also have the potential to use as alternatives as they have higher energy content, octane number and can displace more petroleum gasoline than that of ethanol. Therefore, this study focuses on improvement of different physicochemical properties using multiple alcohols 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. An 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. Tests were conducted under the wide open throttle condition with varying speeds and compared results with that of E15 (Ethanol 15% with gasoline 85%) as well as gasoline. Optimized blends have shown higher brake torque than gasoline. In the terms of BSFC (Brake specific fuel consumption), optimized blends performed better than that of E15. In-cylinder pressure started to rise earlier for all alcohol–gasoline blends than gasoline. The peak in-cylinder pressure and peak heat release rate obtained higher for alcohol gasoline blend than that of gasoline. On the other hand, the use of optimized blends reduces BSCO (Brake specific carbon monoxide) and BSHC (Brake specific hydrocarbon) emission with compared to the use of gasoline and E15. BSNOx (brake specific nitrogen oxides)emission of all alcohol–gasoline blends was higher than that of gasoline. However, MaxR, MaxD, MaxH reduces BSNOx significantly than that of E15. Thus, optimized multi alcohol–gasoline blends were found to be a better option in terms of fuel properties, engine performance, combustion and emission for an unmodified gasoline engine.

1. Introduction

For researchers and manufacturers in the field of energy, the replacement of petroleum gasoline with alternative fuels is an important issue given rising petroleum fuel prices, environmental threats from engine exhaust emissions, fossil fuel depletion, the effects of global warming, and energy concerns [1,2]. Apart from this, researchers are also in quest of alternative fuels for diesel engines, another type of internal combustion engines, which have versatile application compared to gasoline engines [3]. Global energy consumption has increased sharply recently, and it will increase by approximately 53% by 2030, according to the International Energy Agency [4]. The United States Energy Information Administration projects that the liquid fuel consumption in the world will increase from 86.1 million barrels/day to 110.6 million barrels/day by 2035 [5]. 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 [6]. If fossil fuel emissions are not strictly regulated soon, greenhouse gas (GHG) emissions from fossil fuels will increase by 39% by 2030. Hence, alternative fuel sources for clean combustion have received increased attention given several factors, such as worldwide environmental concerns, price hikes in petroleum products, and the expected depletion of fossil fuels [7,8]. Therefore, the development of clean alternative fuels that are locally available, environmentally acceptable, and technically feasible is a global concern. In the transport sector, biofuels can be a good substitute

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Nomenclature

EPA	environmental protection agency	BSFC	brake specific fuel consumption
RON	research octane number	BSCO	brake specific carbon monoxide
RVP	reid vapor pressure	BSHC	brake specific hydrocarbon
HoV	heat of vaporization	BSNOx	brake specific nitrogen oxides
LHV	lower heating value	CO	carbon monoxide
C_2	ethanol	HC	hydrocarbon
C_3	propanol	NOx	nitrogen oxides
C_4	butanol	E15	15% ethanol + 85% gasoline
C_5	pentanol	E10	10% ethanol + 90% gasoline
C_6	hexanol	MaxR	blend of maximum research octane number
MaxH	blend of maximum research heating value	MaxD	blend of maximum research petroleum displacement
SI	spark ignition	rpm	revolution per minute

for fossil fuels because they can be adopted directly without altering the engine and fuelling processes.

The use of alcohols as substitutes for petrol in spark ignition (SI) engines has been investigated extensively. These alcohols enrich oxygen, enhance octane, and reduce carbon monoxide (CO) emission. As an alternative fuel, ethanol is the most widely used alcohol type [9]. It can be combined with gasoline because of its simple chemical structure, high octane number and oxygen content, and accelerated flame propagation [10]. Many experimental studies have confirmed that ethanol increases engine efficiency, torque, and power. However, its brake specific fuel consumption (BSFC) is higher than that of gasoline [11].

In many countries, governments mandate the integration of ethanol with gasoline. The Environmental Protection Agency (EPA) issued a waiver that authorizes the incorporation of up to 15% ethanol into gasoline for cars and light pickup trucks made in 2001 onwards [12]. The US Renewable Fuel Standard mandates the production of up to 36 billion gallons of ethanol and advanced bio-fuels by 2022 [13]. To meet the high demand for ethanol, alcohols with increased carbon numbers can be utilized as enhanced alternatives because the use of ethanol as fuel in gasoline engines is mainly limited by its low heating value (LHV). Hence, additional low-LHV fuel must be generated to match a certain power level [14]. Alcohols with high carbon numbers, such as propanol and butanol, have a higher LHV than ethanol. On the other hand all of these alcohols can be produced from coal-derived syngas that is a renewable source [15]. 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 number alcohols [16]. 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 [17,18].

Some studies have compared different alcohol–gasoline blends. Gravalos et al. [19] integrated approximately 1.9% methanol, 3.5% propanol, 1.5% butanol, 1.1% pentanol, and variable concentrations of ethanol with gasoline in a single-cylinder gasoline engine. A total of 30% alcohol was incorporated into the gasoline. The alcohol–gasoline blend emitted less CO and HC but more NOx and CO_2 than pure gasoline. In the present study, multiple alcohol–gasoline blends also emit more acceptable levels of CO and HC than the ethanol–gasoline blend. Yacoub et al. [20] integrated methanol, ethanol, propanol, butanol, and pentanol with gasoline in an engine and analyzed its performance and emissions. Each alcohol was blended with gasoline containing 2.5% and 5% oxygen. The alcohol–gasoline blend displayed better BTE, knock resistance, and emissions than gasoline, but its BSFC was higher. Alcohols with low carbon content (e.g. C1, C2, and C3) contain high levels of oxygen. Hence, relatively less of these alcohols are required to reach the targeted oxygen percentage than alcohols with high carbon content (e.g., C4 and C5). Alcohol percentage and properties varied across blends. Thus, different alcohol–gasoline blends cannot be compared properly under optimized oxygen concentrations. Gautam et al. [21] prepared six alcohol–gasoline blends with various proportions of methanol, ethanol, propanol, butanol, and pentanol that total 10% alcohol. The alcohol–gasoline blends emitted lower brake specific CO, CO_2, and NOx than pure gasoline. However, they did not blend alcohols in any specific volume percentage or considering fuel properties.

Engine performance, combustion and emission are directly affected by the physicochemical properties of fuel. However, no research has been done considering to improve fuel properties of the multi alcohol gasoline blend. There is a lack of research on optimization of fuel properties of multiple alcohol–gasoline blends and their effect on engine performance, combustion and emission. Other hand, these days many research are going on producing higher carbon number alcohols from renewable sources [22–26]. 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, combustion and emission with respect to E15 and gasoline.

2. Materials and method

2.1. Fuel selection

In this study, we choose ethanol, propanol, butanol, pentanol and hexanol (99.8% purity). We utilized branched isomers of propanol, butanol and pentanol as they have higher octane numbers. However, straight (n-) isomer for hexanol was used due to its low cost compared to iso-hexanol. We procured the ethanol from Chemical Industries (Malaya) Sdn. Bhd., Malaysia and the other alcohols from QREC Chemical Company, Thailand. We obtained Primax 95 gasoline with research octane number (RON) 95 from PETRONAS, Malaysia as the base gasoline.

2.2. Measurement of fuel properties and prediction method

To identify the optimum blend, we must determine the physicochemical properties of alcohol–gasoline blends in relation to engine operation. In the evaluation of fuel, density, LHV, HoV,

Table 1
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	

RON, and Reid vapor pressure (RVP) are crucial to customer satisfaction, engine and legislative requirements, and the maintenance of industry standards. Thus, these fuel properties were compared in fuels containing volumetric amounts of different alcohols, including E15. In this experiment, fuel properties were measured using different apparatuses, as detailed in Table 1. Fuel RON was provided by the suppliers, and Table 2 lists the properties of the gasoline and other alcohols.

Under basic assumptions regarding the mixture, we directly calculated some of these properties, including density, LHV, HoV, and oxygen content. These calculations remain straightforward regardless of the number of components in the blend because the properties of these components are linearly combined. However, other properties are difficult to compute, including distillation profile, RON, and RVP. Thus, we describe the calculation process of these non-linear properties in this section.

The properties of the blend components are linearly related to density, LHV, HoV, and oxygen content. Hence, we use Eq. (1) to compute these properties.

$$\text{property}_{\text{blend}} = \sum_{i=1}^{n} v_i \times \text{property}_i \tag{1}$$

The volumetric integration of alcohol with gasoline nonlinearly modifies octane number [27]. Therefore, Anderson et al. [28] suggested molar alcohol concentration as a more appropriate measure to describe the dependence of RON and motor octane number on alcohol content. They simplify the calculation of RON by considering the molar fraction of alcohol in a blend. In Eq. (2), x_{alc} is the molar fraction of alcohol in the blend.

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

The vapor pressure of the ethanol–gasoline blend is difficult to estimate because its solution is complex and non-ideal. To predict this pressure, Reddy [29] developed a model using the UNIFAC method. We apply this model in the current study. The curves of the alcohols with high carbon number (C_3–C_6) are drawn based on experimental data and extrapolated in the alcohol–gasoline blend to predict the RVP in the blend. Fig. 1 displays the estimated and experimental vapor pressures of different alcohol–gasoline blends.

The blend properties were optimized using Microsoft Excel solver tools. This optimizer solves linear, non-linear, and integer programs within the spreadsheet. In the spreadsheet, the fuel volume concentrations were designated as decision variables, and volume concentration was changed to obtain the desired properties. The equations used to predict the properties were inputted into Excel solver tools. We will describe the target values in the next chapter. The three best combinations of fuel from among the optimized combinations were considered for maximum heating value, RON, and petroleum displacement. In unmodified engine, high LHV is very much desired for better performance where the RON of traditional ethanol–gasoline blend is sufficient and very high RON will not improve engine performance though. Moreover, MaxR is focused for using in modified engine like an engine with higher compression ratio as because higher RON is recommended to use in that type of engine to avoid knocking. If consumers want to replace more petroleum fuel by renewable fuel then they can choose MaxD blend. MaxD blend will replace more than 15% petroleum fuel with satisfying all the fuel properties of traditional ethanol–gasoline blend. Finally the blends were prepared according to optimum blend ratio and the blends were tested in lab.

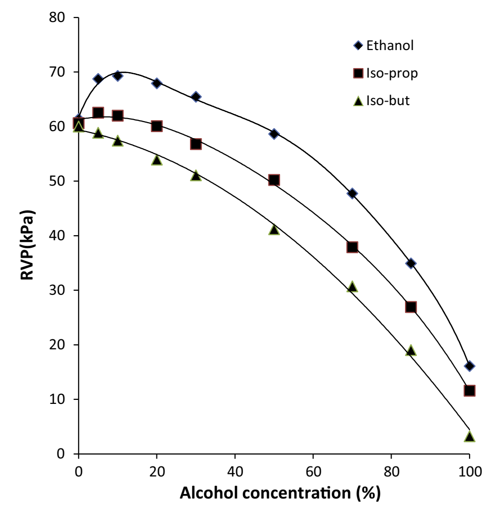

Fig. 1. Estimated gasoline–alcohol blend RVP.

2.3. Target properties for optimum blends

To evaluate the prospect of a substance as a fuel, it must first fulfill the desired properties. Hence, the total alcohol content of a multiple alcohol–gasoline blend must fall within a certain range.

Table 2
Properties of fuels.

Property	Unit	Gasoline	Ethanol	Iso-propanol	Iso-butanol	Iso-pentanol	n-hexanol
Oxygen	wt.%	0	34.7	26.6	21.6	18.1	15.7
Density	kg/m^3	736.8	775.4	789.4	806	812.5	822.2
LHV	MJ/kg	43.919	28.793	32.947	35.689	37.622	38.968
RON		95	107.4	112.5	105.1	98.8	69.3
RVP (at 37.8 °C)	kPa	63.9	19.1	13.8	6.6	2.9	2.8
HoV	kJ/kg	349	923	761	683	621	484
Specific gravity	–	0.7375	0.7754	0.7899	0.8067	0.8132	0.8229

Table 3
Target value of optimum blends.

Properties	Unit	Alternative fuel's target
LHV	MJ/kg	⩾41.65
RON	–	⩾96.24
RVP	kPa	34–62
Oxygen content	wt.%	⩽5.205
Petroleum displacement	vol.%	⩾15%

Table 4
Specification of the tested engine.

Engine parameter	Value
Number of cylinder	4
Displacement volume	1596 cm^3
Bore	78 mm
Stroke	84 mm
Connecting rod	131 mm
length	131 mm
Compression ratio	10:1
Max output	78 kW at 6000 rpm
Max torque	135 N-m at 4000 rpm

In this study, the fuel properties considered are energy content, octane number, oxygen content, petroleum displacement, and vapor pressure. Once these criteria and their target values are implemented, the properties of the multi-component blends are predicted and compared with those targets. We then examine the compositions of blends whose properties meet all of the target criteria. The trends are then identified and discussed in this paper.

The E10/E15 alternate scenario aims to identify multi-component blends that can be used in current engines and can enhance petroleum displacement, knock resistance, and/or energy content compared with E10/E15 while adhering to industry standards and consumer expectations. These blends contain adequate oxygen content to meet the EPA E15 waiver, a knock resistance equivalent to that of E10 or higher, vapor pressure that is within the standards of the American Society for Testing and Materials, a minimum energy content equal to that of E15, and petroleum displacement that is at least equal to that of E15. Table 3 summarizes these criteria and their values.

2.4. Experimental setup

We experimented on a four-cylinder gasoline engine at the Engine Laboratory of the Mechanical Engineering Department in the University of Malaya. Table 4 details the engine, and Fig. 2 depicts the schematic of the experimental setup. The test engine was coupled with an eddy current dynamometer (Froude Hofmann model AG150, United Kingdom) with a maximum power of 150 kW. The engine was first operated on gasoline for a few minutes to stabilize the operating condition. The fuel was then changed to the alcohol blend. After sufficient amounts 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.

The engine was operated between 1000 rpm and 6000 rpm with a step of 1000 rpm at 100% load condition. We measured fuel flow using a KOBOLD ZOD positive-displacement type flow meter (KOBOLD, Germany). The data were automatically collected using the CADET 10 data acquisition system. Exhaust emissions were measured using the AVL DICOM 4000 exhaust gas analyzer (AVL DiTEST, Austria), where CO and HC are determined by infrared measurement detector and NOx determined by electrochemical measurement detector. For combustion analysis a pressure sensor and a crank angle encoder (RIE-360) have been used. These two sensors together provide the in-cylinder pressure variation with crank angle. Digital data have been recorded in a computer using a software name DEWESoft Combustion Analyzer. In each test, performance, combustion and emission were measured in triplicate. These measurements were highly repeatable within the test series.

3. Calculation methods

3.1. Engine performance

The engine performance is evaluated on torque and BSFC. The BSFC were calculated by following equations:

$$\text{BSFC} = \frac{\text{Fuel Consumption}}{\text{Output Power}} \tag{3}$$

3.2. Error analysis

Errors and uncertainties in the experiments can arise from instrument selection, condition, calibration, environment, observation, reading, and test planning. Uncertainty analysis was required to prove the accuracy of the experiments. The measurement range, accuracy and percentage uncertainties which associated with the instruments used in this experiment are listed in Table 5. To compute the overall percentage uncertainty due to the combined effect of the uncertainties of various variables, the principle of propagation

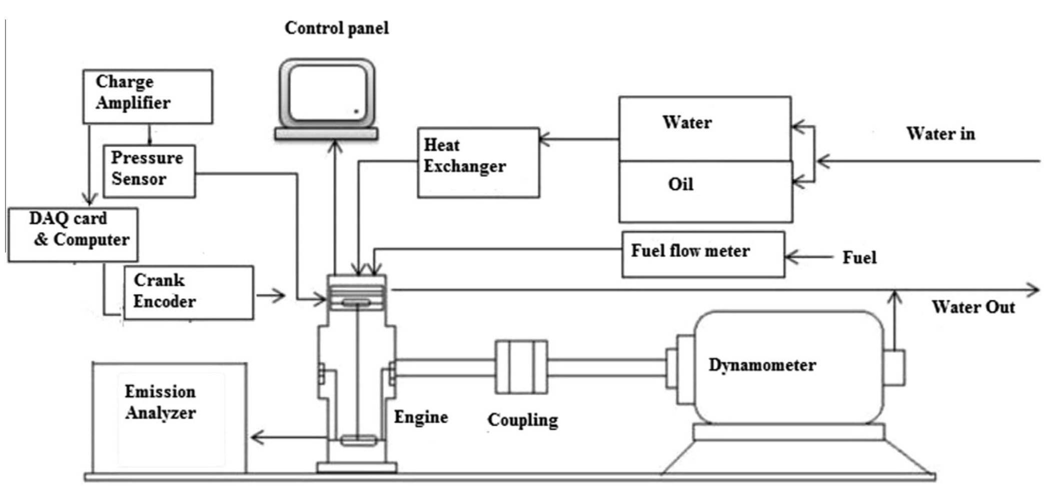

Fig. 2. Schematic diagram of the engine test bed.

Table 5
List of measurement accuracy and percentage uncertainties.

Measurement	Measurement range	Accuracy	Measurement techniques	Uncertainty (%)
Load	±600 Nm	±0.1 Nm	Strain gauge type load cell	±0.25
Speed	0–10,000 rpm	±1 rpm	Magnetic pick up type	±0.1
Time		±0.1 s		±0.2
Fuel flow measurement	0.5–36 L/h	±0.04 L/h	Positive displacement gear wheel flow meter	±0.5
Air flow measurement	0.25–7.83 kg/min	±0.07 kg/min	Hot-wire air-mass meter	±2
CO	0–10 vol.%	±0.01 vol.%	Non-dispersive infrared	±1
HC	0–2000 ppm	±1 ppm	Heated flame ionization detector	±1
NOx	0–5000 ppm	±1 ppm	Electrochemical	±1.3
Smoke	0–100%	±0.1%	Photodiode detector	±1
EGT sensor	0–1200 °C	±0.3 °C	Type K thermocouple	±0.15
Pressure sensor	0–25,000 kPa	±10 kPa	Piezoelectric crystal type	±0.5
Crank angle encoder	2–12,000 rpm	±0.125°	Incremental optical encoder	±0.03
Accelerometer	±490 m/s^2	±5 m/s^2	Piezoelectric shear mode accelerometer	±1
Computed				
BSFC		±5 g/kW h		±1.5
BSCO		±0.05 g/kW h		±0.7
BSHC		±0.05 g/kW h		±0.7
BSNOx		±0.1 g/kW h		±2.5

Table 6
Composition of optimized fuels.

Blend name	Blend specialty	Composition
MaxR	Blend with maximum RON	19.57% Propanol 80.43% Gasoline
MaxH	Blend with maximum LHV	8.58% Propanol 5.7% Butanol 1% Pentanol 84.72% Gasoline
MaxD	Blend with maximum Petroleum displacement	4.8% Ethanol 9.61% Propanol 5.44% Pentanol 80.15% Gasoline

of errors is considered and can be estimated as ±3.13%. The overall experimental uncertainty was computed as follows [30]:

Overall experimental uncertainty = Square root of [(uncertainty of speed)^2 + (uncertainty of torque)^2 + (uncertainty of BSFC)^2 + (uncertainty of pressure sensor)^2 + (uncertainty of crank angle encoder)^2 + (uncertainty of BSCO)^2 + (uncertainty of BSHC)^2 + (uncertainty of BSNOx)^2 = Square root of $[(0.1)^2 + (0.25)^2 + (1.5)^2 + (0.5)^2 + (0.03)^2 + (0.7)^2 + (0.7)^2 + (2.5)^2] = 3.13$.

4. Result and discussion

4.1. Optimum blend properties

Confirming the target values described in Table 3, properties prediction equations (described in Section 2.2) were used in an optimization tool of Microsoft Excel to find the optimum fuel blend ratio. The optimized tool was programmed for finding three different blend ratio by focusing on maximum LHV, RON, and petroleum displacement with confirming all target values and denoted by MaxH, MaxR, and MaxD, respectively. Table 6 depicts the blend ratio of these suitable blends. The properties of these three blends were measured experimentally and results are given in Table 7. It is seen that all three blends met the targeted alternative fuel properties as described in Table 3. Compared with the target value, the MaxR blend improves RON by 4.65%, improves LHV by 0.29% and displace 30.47% more gasoline than E15. MaxH blend, which focuses to improve fuel LHV, improves LHV by 1.92% than E15 with met all other fuel properties target values. MaxD blend improves 32.27% petroleum displacement with improving 0.35% RON and 0.36% LHV than target values.

Table 7
Properties of optimum fuels and improvement over target.

	Expected value	MaxR	MaxH	MaxD
RON	⩾96.24	**100.71** (+**4.65**%)	96.24 (0%)	96.58 (+0.35%)
LHV	⩾41.65	41.77 (+0.29%)	**42.45** (+**1.92**)	41.8 (+0.36)
Petroleum displacement	⩾15	19.57 (30.47%)	15.28 (+1.8)	**19.85** (+**32.27**)

Bold fonts indicate the main focused properties of corresponding fuel.

4.2. Engine performance

4.2.1. Torque

Torque is a turning force produced by the pressure from the crankshaft of the piston. Engine torque depends on engine stroke length, charge condition, and average effective cylinder pressure [31]. Under a constant engine condition, torque varies given different fuels as a result of the fuel properties and the effective pressure generated. Fig. 3 compares the engine torque given the test fuels. On average, alcohol–gasoline blends increase torque 1.9%, 1.82%, 1.13% and 2.57% for MaxR, MaxD, MaxH and E15 fuel respectively than that of gasoline. The increased torque may be attributed to the high latent heat of vaporization (HoV). Fuel vaporizes in the intake manifold and in the combustion chamber. When the HoV of alcohol increases, charge temperature is decreased 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 [32,33]. Moreover, the incorporation of oxygenated alcohol produces a lean mixture that burns more efficiently than gasoline [11]. Balki and Sayin [34] explained higher flame speed of alcohol is the reason of better torque of alcohol–gasoline blend. However, among all blends, E15 obtained the highest torque, though it has lowest LHV than that of other blends. This improved torque may be attributed to the enhanced RON of E15. High RON aggravates ignition delay, which decelerates energy release rate and limits heat loss from the engine because the heat from the cylinder is not transferred to the coolant in time [15]. MaxR also produce nearly the same torque as E15. Hence, engine torque decreases after it is maximized by engine acceleration.

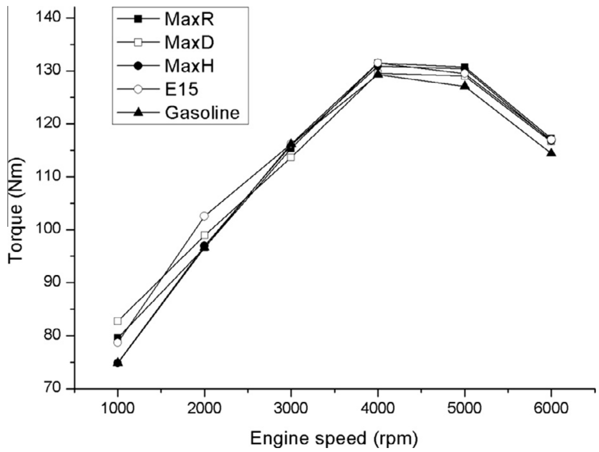

Fig. 3. Variation of Torque with engine speed.

4.2.2. Brake specific fuel consumption

Fig. 4 depicts the influence of test fuels on BSFC at different engine speeds. 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. On average, the BSFC values of E15, MaxR, MaxD and MaxH were higher than that of gasoline by 6.7%, 2%, 4.76% and 4.26%, respectively. This result is typically ascribed to the low energy content of the alcohols, which enhances engine BSFC when it is applied without any engine modification [35]. Therefore, increased amounts of fuel are required to produce the same level of engine power as that generated by low LHV fuel. The high BSFC of alcohol may also be induced by high alcohol density [11]. Nonetheless, the BSFC of MaxR is closer to that of gasoline than the other alcohols. Furthermore, MaxR, MaxH and MaxD displayed BSFC values that were 5.1%, 0.5% and 1.4% lower, respectively, than that of E15. 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.

4.3. Engine combustion

4.3.1. In-cylinder gas pressure

We can compare the combustion characteristics of different fuels based on cylinder gas pressure and heat release rate. Fig. 5 compares the cylinder gas pressures of all of the test fuels at an engine in full throttle load at a speed of 5000 rpm. All of the fuels displayed similar inlet and exhaust pressure curves because throttle angle was

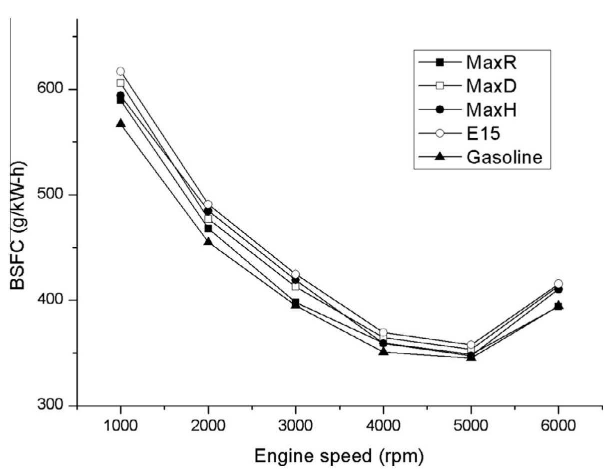

Fig. 4. Variation of BSFC with engine speed.

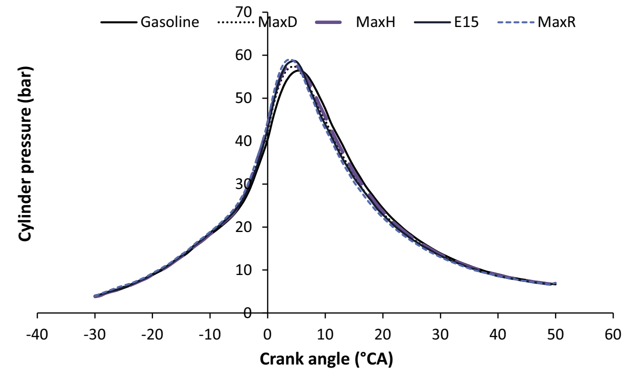

Fig. 5. Comparison of in-cylinder pressure at 5000 rpm.

almost constant. Furthermore, the maximum pressures for all test fuels were close to the top dead center (TDC). As observed in the figure, cylinder gas pressure started to increase earlier in alcohol–gasoline blends than in pure gasoline. Furthermore, this pressure was higher for alcohol–gasoline blend than pure gasoline. According to Melo et al. [36], the increase in alcohol enhanced timing and prevented knocking, thus maximizing the pressure obtained using alcohol. Balki et al. [35] added that high latent HoV and oxygen content in alcohols increases cylinder gas pressure. Moreover, Fig. 5 shows that the addition of alcohol shortens combustion duration compared with that of gasoline. This finding is attributed to high laminar flame speed and RON by Balki et al. [35].

4.3.2. Heat release rate

Fig. 6 illustrates the effect of blends on the rate of heat release to the crank angle at an engine speed of 5000 rpm. At high rates, alcohol accelerates combustion flame speed, particularly in the MaxR combustion. According to Siwale [37], flame burned more quickly in alcohol–gasoline blends than in pure gasoline. Moreover, the peak release rate of location heat is higher in the alcohol–gasoline blend than in pure gasoline. Eyidogan et al. [38] explained that the oxygen content in alcohols improves combustion; thus, much fuel burns near TDC. This condition enhances the peak release rate of location heat in alcohol.

4.4. Engine emission

4.4.1. BSCO 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 [39]. Fig. 7 shows, the variation of BSCO exhaust emission in relation

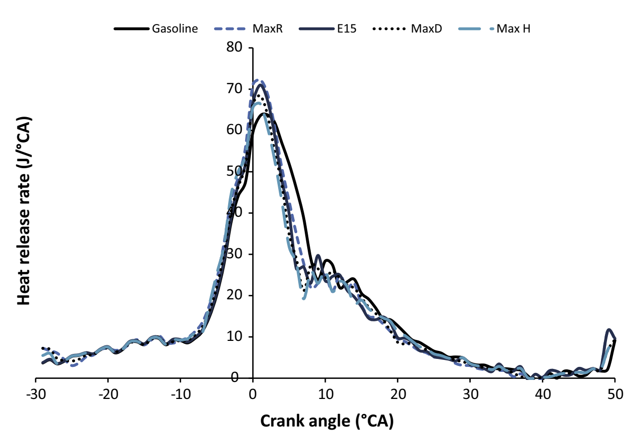

Fig. 6. Comparison of heat release rate at 5000 rpm.

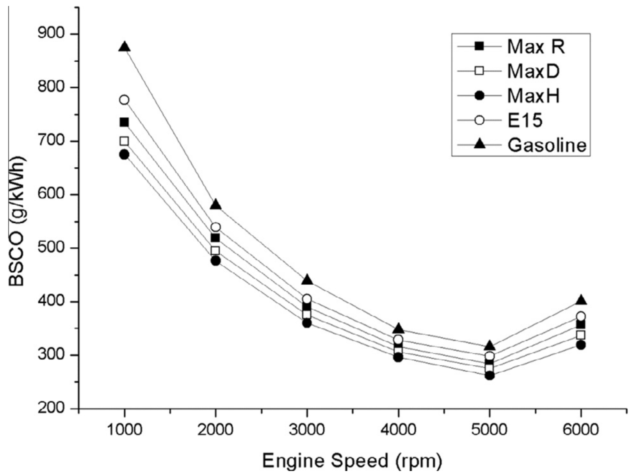

Fig. 7. Variation of BSCO emission with engine speed.

to the engine speed. In overall engine speed range, BSCO is significantly lower for alcohol–gasoline blends than that of gasoline fuel. Alcohols are oxygenated fuels; therefore, they enhance oxygen content in fuel for combustion. This process generates the "leaning effect", which sharply reduces CO emission [40]. This result can also be attributed by the higher flame speed of alcohol that assists to complete the combustion [33,41]. As a result of this increased flame speed in alcohol, alcohol–gasoline blends complete combustion earlier and emit less CO. It was observed that the minimum BSCO emissions obtained from the gasoline, E15, MaxR, MaxH and MaxD fuels were 316.04 g/kW h, 298.22 g/kW h, 262 g/kW h, 275.5 g/kW h and 284.15 g/kW h respectively, and were achieved at 5000 rpm engine speed. Comparing all alcohol–gasoline blends, it is seen that optimized blends results slightly lower BSCO than E15. Using MaxR, MaxH and MaxD reduce BSCO than E15 by averages of 4.4%, 9.66%, 8.52% and 12.1%, respectively. Higher LHV of MaxH blend accelerates the combustion process that results in low CO emission. Gravalos et al. [19] also found lower CO emission for lower-higher molecular mass alcohol–gasoline fuel blends than that of lower molecular mass alcohol/gasoline blend.

4.4.2. BSHC 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 [42]. Fig. 8 exhibits the emissions of BSHC by all test fuels at speeds ranging from 1000 rpm to 6000 rpm. These emissions were slightly lower in all alcohol–gasoline blends than in pure gasoline. On average, emissions of BSHC by E15, MaxR, MaxD and MaxH decreased by 5.49%, 1.0%, 9.8% and 9.3%, respectively. This result may be attributed to the leaning effect and the oxygen content in the alcohol [11]. At the same time, laminar flame speed of alcohol is higher than gasoline [43]. That may assist complete combustion of alcohol–gasoline blend as well as lower HC emission. Moreover, these emissions decrease as engine speed increase in all blends. At high speeds, the air–fuel mixture homogenizes to increase in-cylinder temperature. This condition in turn enhances combustion efficiency. Thus, BSHC emission was lower at high engine speeds than at low speeds. This conclusion is consistent with that of Koc et al. [11]. In overall speed range, for all alcohol–gasoline blends, BSHC were quit similar. BSHC emission of optimized blends varies 5–9% than E15 blend.

4.4.3. BSNOx emission

During combustion at high temperature, nitrogen in the air oxidizes to form NOx. Thus, the generation of NOx in an engine

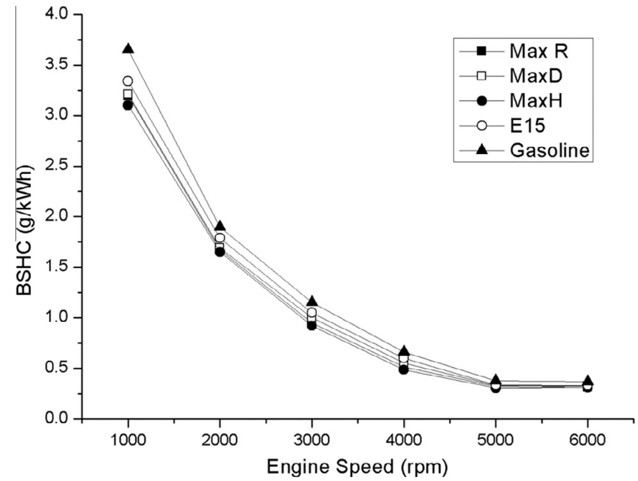

Fig. 8. Variation of BSHC emission with engine speed.

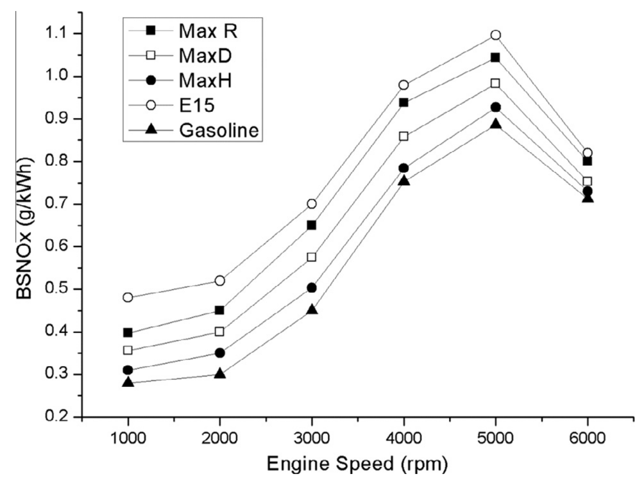

Fig. 9. Variation of BSNOx emission with engine speed.

is closely related to combustion temperature, oxygen concentration, and residence time inside the combustion chamber [44]. Fig. 9 exhibits the variation in BSNOx emission at WOT and at different engine speeds. As per the study result, NOx emission is higher for alcohol–gasoline blends than that of pure gasoline. It is seen that E15 produced the highest NOx emission. The highest BSNOx is observer at 5000 rpm and it was 1.04 g/kW h, 0.98 g/kW h, 0.92 g/kW h, 1.1 g/kW h and 0.89 g/kW h for MaxR, MaxD, MaxH, E15 and gasoline respectively. In general, NOx emission depends on the peak in-cylinder temperatures and oxygen concentration of fuel [19]. Alcohol–gasoline blends result higher peak in-cylinder pressure than gasoline (in Fig. 5) that indicates higher peak in-cylinder temperatures for alcohol–gasoline blends. And also higher oxygen concentration might be the reason for higher NOx emission for using alcohol gasoline blend [45]. However, optimized blends emit lower BSNOx as compared to the use of E15. Higher BSFC together with higher torque of E15 increases the in-cylinder temperature as well as more BSNOx emission than that of other fuels.

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, combustion and emission 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 than gasoline. Higher oxygen content and high latent heat of vaporization of alcohols may be the reason of more torque for alcohol blended fuel. As expected, the BSFC was generally increased with the use of alcohol–gasoline blends with compared to the use of gasoline. However, MaxR, MaxD and MaxH blends reduced BSFC 5.1%, 0.5% and 1.4% respectively than that of E15 fuel.
- For faster flame speed of alcohols, in-cylinder gas pressure and heat released rate started increase earlier for all alcohol gasoline blends than that of using gasoline fuel. Combustion duration of alcohol–gasoline blends was shorter than gasoline. Peak in-cylinder pressure and peak heat release rate also higher for alcohol gasoline blends than pure gasoline fuel and highest was for MaxR blend.
- All alcohol gasoline blends emitted significantly lower BSCO and BSHC emission than that of gasoline. BSNOx emissions of alcohol–gasoline blends were higher than gasoline whereas ethanol shows highest NOx emission among all test fuels. MaxR, MaxD and MaxH reduced 6.9%, 14.6% and 21.5% BSNOx emission than that of E15.
- The overall results showed that optimized blends have improved fuel properties and shows better performance and emission in gasoline engine without any modification. Thus optimized blends can be used with better engine performance and emission 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.

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