Experimental investigation of butanol gasoline blends effect on the mass fraction burned in a spark ignition engine

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Abstract— **The growing energy demand and the limitation of the fossil fuels force the transportation sector to seek for alternative energy sources. Butanol has emerged as one of the potential alternative energy solution especially for spark ignition engines. Experimental study on engine combustion characteristics particularly on mass fraction burned (MFB) of spark ignition engines fueled with secondary butyl alcohol (sec-butanol) gasoline blends was carried out. Engine was operated at engine speeds 3500 RPM with 50% of wide throttle open (WTO) for each blend (5%, 10% and 15% volume of sec-butanol) and neat gasoline. The in-cylinder pressure data were collected and the average cycle was integrate to obtain MFB profiles. Based on the MFB results at using sec-butanol gasoline blends is always taken higher value of degree of crank angle compared to gasoline fuels. However, throughout the analysis, by addition of 15% of volume in gasoline fuels reduced the 10 – 90% early flame propagation, 10 – 90% combustion duration and early position of degree of crank angle at 50% of MFB for 1.7%, 4.5% and 5.9% respectively with respect ot gasoline fuels.**

Index Terms— sec-butanol, gasoline fuels (G100), mass fraction burned (MFB)

I. INTRODUCTION

Energy security is an increasing critical issues due to the potential of fossil fuels dearth in near future [1]. As in consequences, the global energy consumption brings adverse effect toward environment and human health [2]. In 2013, the most consumed energy came from non-renewable energy which accounted for 82.67% among other energy sources in which crude oil, coal and natural gas by 30.92%, 28.95% and 22.81% respectively [3]. The petroleum fuels play a key factor especially in transportation area to meet the basic necessity of human needs. In order to combat the scarcity of petroleum fuels particularly in transportation areas a more efforts need to be done to find clean and sustainable alternative fuel [4].

Gasoline engines are mostly the best choices for private and commercial used [5]. The use of oxygenated fuels in gasoline engines has a great potential of reducing the dependency of the petroleum fuels [6]. The main oxygenated alternative fuel used is alcohols mainly from ethanol for operation of gasoline-type vehicles [7]. However, for the past few years, the investigation of ethanol has received considerable critical attention with less attention paid to the butanol as a sustainable alternative fuel.

Butanol is consider as an advanced alternative biofuel [8, 9]. Butanol is a four carbon atom alcohol with chemical formula of $C_4H_{10}O$ [10]. There are four types of butanol isomers categorized as n-butanol, sec-butanol, tert-butanol and iso-butanol [11, 12]. Each butanol is recognized based on their hydroxyl attached to one of the carbon atoms [13]. Each of these isomers have different physical and chemical properties [14]. As compared to ethanol, butanol is the most similar fuel properties to the gasoline fuel such as lower heating value, stoichiometric air-fuel ratio, research octane number and auto ignition temperature, thus, making it more appropriate to be blended with gasoline fuels [15-17].

In recent years, there has been an increasing amount of literature on butanol application used as the fuel substitutes to the gasoline fuels. Alasfour [18] studied the emission particularly on NO_x emissions using of 30% by volume of butanol blended with gasoline fuels. Irimescu [16] used 50% by volume of iso-butanol mixed with gasoline fuels to investigate the effects of fuel conversion efficiency. It was find out that a slight improvement of fuel conversion efficiency up to 6% when the engine was operated by the blended fuels compared to gasoline fuels. Pechout [19] evaluated the effect of higher level butanol blends by 30% and 50% on combustion characteristics of an unmodified gasoline engines. Based on their results, flame combustion propagation was quicker with butanol blended fuels.

The importance of mass fraction burned analysis is to provide a useful account of how the combustion develop through several stages. There are three stages of the mass fraction burned: (1) flame development angle; (2) Rapid burning angle; and (3) overall burning angle [20]. The literature has emphasized the

importance of analysis of mass fraction burned using various alternative fuels. In an analysis of mass fraction burn, Smith et al. [21] found that addition of hydrogen of approximately 25%, resulted to higher peak of the mass fraction burned. However they also noted that at higher mass fraction burned the knock phenomenon occurred. Similarly, Szwaja et al. [22] found that combustion knock phenomenon are due to greater peak of the mass fraction burn. Bonatesta et al. [23] had develop an empirical function for the 0 to 90 per cent mass fraction burned to define according to Wiebe function.

The present study was designed to determine the effects of sec-butanol gasoline blends by 5%, 10% and 15% by volume of sec-butanol in gasoline fuels towards combustion characteristics particularly on mass fraction burned (MFB) analysis. This work contributes to extend existing knowledge of combustion characteristics of the blended fuels by sec-butanol. This investigation will performed particularly on; mass fraction burned, 0-10% MFB, 50% and 10-90% MFB.

II. EXPERIMENTAL SETUP

A. Materials

Gasoline RON 97 denoted as G100 was selected as the reference fuels and analytical grade of secondary butyl-alcohol (sec-butanol) with purity of 99.5% was used in this study. Sec-butanol was mixed with reference fuels using mechanical automatic stirrer in the ratio of 5%, 10% and 15% by volume of sec-butanol, which are referred as GBu5, GBu10 and GBu15 respectively. Table I lists the main properties of sec-butanol and gasoline fuels.

TABLE I. PROPERTIES OF GASOLINE AND SEC-BUTANOL [24, 25, 8]

Property	Gasoline	Sec-butanol
Molar C/H ratio	0.44 – 0.50	-
Density (g/cm^3 at 20°C)	0.72 – 0.76	806.3
Lower heating value (KJ/kg)	44, 300	33, 000
Stoichiometric air/fuel ratio	14.6	11.1
RON/MON	95/85	101/32
Auto – ignition temperature (°C)	228 – 470	406.1
Boiling point (°C)	27 – 225	99.5
Heat of vaporization (KJ/Kg)	349	551
Flammable limits (%volume)	1.4 – 7.6	1.7 – 9.8
Laminar flame speeds [26]	~33	~48

B. Description of experimental setup

Experiments were conducted on a Mitsubishi 4G93 four-cylinder, four-stroke, water-cooled, port-fuel-injection spark ignition (SI) engines using sec butanol gasoline blends as test fuel and gasoline as baseline fuel. The experiments on SI engines were conducted without making any modification in the engine hardware. The technical specifications of the test engine are given in Table II. Actual engine test bed and the schematic diagram of the experimental setup are shown in Fig. 1. The relative air fuel ratio was taken using an accurate calibrated KANE gas analyzer version autoplus 5-2. Air flow through the intake was measured using Benetech GM8903 hot wire type anemometer with the air speeds resolution by 0.001 m/s. A total of seven thermocouples was mounted at; intake exhaust, fuel line and outlet engine cooling; in order to control the engine surrounding temperatures. Engine cylinder number one was attached with the in-cylinder pressure sensor to measure instantaneously in-cylinder pressure of the engine using Kistler piezoelectric in-cylinder pressure transducer 6125B spark plug type with a measuring rate of 0–200 bars and a sensitivity of ~-10 pC/bar. The crank angle signal was acquired with Kistler 2613B1 crank angle encoder, and the in-cylinder combustion pressure was recorded simultaneously using DEWE-Combustion analyzer provided from DEWE-5000 series data acquisition system. It should be mentioned that the spark timing of the engine was not controlled, however throughout the analysis the spark timing occurred nearly at 0°crank angle. Fuels were tested in this order: gasoline, GBu5, GBu10 and GBu15. Following each fuel change, the engine was operated for about 15 to 20 minutes at intermediate RPM using gasoline fuels. This was done to flush the fuel system to avoid fuel injector clogged especially when using sec-butanol gasoline blends. Each experiment was repeated three times and the measured

experimental value were averaged. Tests were conducted at single engine speeds of 3500 RPM with 50% of wide throttle open. Engine speed of 3500 rpm has been emphasize in this study since it is the regular operating engine speed for most of the engine.

TABLE II. ENGINE SPECIFICATIONS

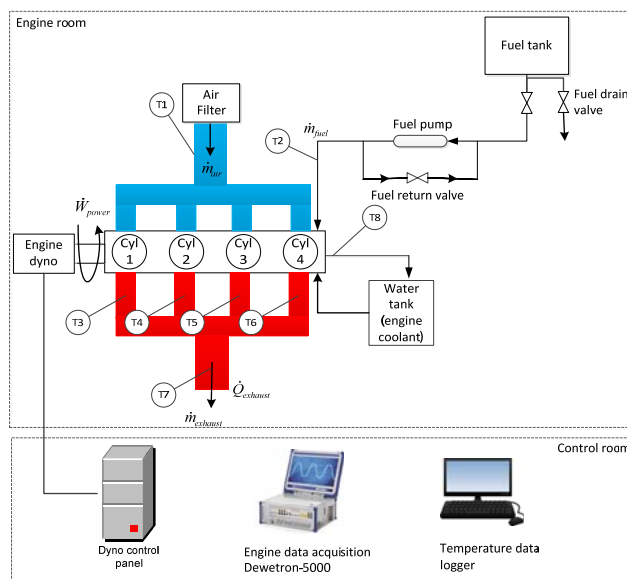| Engine Descriptions	
Bore x Stroke	81.0mm x 89.0mm
Piston Displacement	1834cc
Compression Ratio	9.5:1
Fuel injection type	ECI-Multi (Electronically Controlled Multi-point Fuel Injection
Max Power	86kW @ 5500rpm
Max Torque	161Nm @ 4500rpm
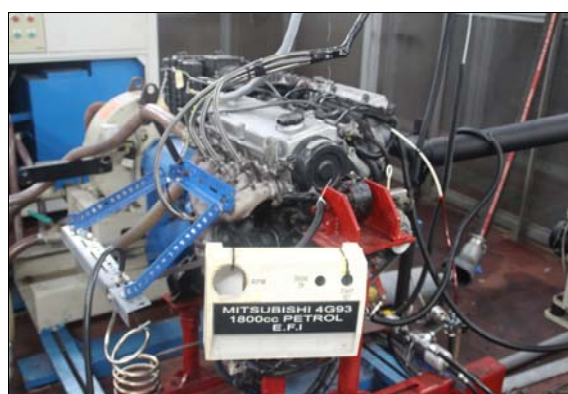
Fig. 1. Engine test bed

Fig. 2. Schematic diagram

C. Mass fraction burned analysis

Mass fraction burned (MFB) for the fuel signifies the percentage quantity of fuel that has been combusted within the cylinder in certain combustion duration [20]. Chemical energy Q_{ch} released by combustion can be determine on the foundation of the first law of thermodynamics as a function of crank angle θ .

$$Q_{ch} = \int_{\theta} \left(\frac{\gamma}{\gamma - 1} p \frac{dV}{d\theta} + \frac{1}{\gamma - 1} V \frac{dp}{d\theta} \right) d\theta \qquad (1)$$

Where γ is the polytropic index, p is the in-cylinder pressure, V is the cylinder volume and θ is the engine crank angle. Mass fraction burned (MFB) in each individual engine cycle is a normalized quantity with a scale of 0 to 100%, describing the process of chemical energy release as a function of crank angle. The determination of MFB is commonly based on burn rate analysis. The assumption was made that, during engine combustion, the pressure rise Δp consists of two parts: pressure rise due combustion (Δp_c) and pressure change due to volume change (Δp_v):

$$\Delta p = \Delta p_c + \Delta p_v \qquad (2)$$

Assuming that the pressure rise Δp_c is proportional to the heat added to the in-cylinder medium during the crank angle interval, the mass fraction burned may be calculated as:

$$MFB = \frac{m_b(i)}{m_b(total)} = \frac{\sum_0^i \Delta p_c}{\sum_0^N \Delta p_c} \qquad (3)$$

Where i is the consider combustion interval and N is the is the total number of crank intervals [27].

III.   RESULT AND DISCUSSIONS

In this presence research investigation, the quantity of GBuX represents a blend consisting of X% of sec-butanol by percentage of volume, e.g., GBu5 indicates a blend consisting of 5% of sec-butanol in 95% of gasoline. Four test fuels were emphasized in this study: gasoline (G100); 5% of 2-butanol (GBu5); 10% of butanol (GBu10); and 15% of (GBu15). In Fig. 1 indicates the normalized mass fraction burned (MFB) with respect to crank angle degree at 3500 RPM with 50% of wide throttle open (WTO). The MFB profile is a key elements of combustion for the fuel to represents the burning amount of fuel percentage combusted in the combustion chamber in certain combustion duration [28]. This parameter highly depends on the ignition delay period and peak in cylinder pressure for different tested fuels. Based on the Fig. 3, the highlighted area represents the zoom area specified at 0 – 10%, 50% and 10 – 90% of MFB. At all of MFB conditions it can be said that G100 fuels are the nearest to the top dead center followed by GBu15, GBu10 and GBu5.
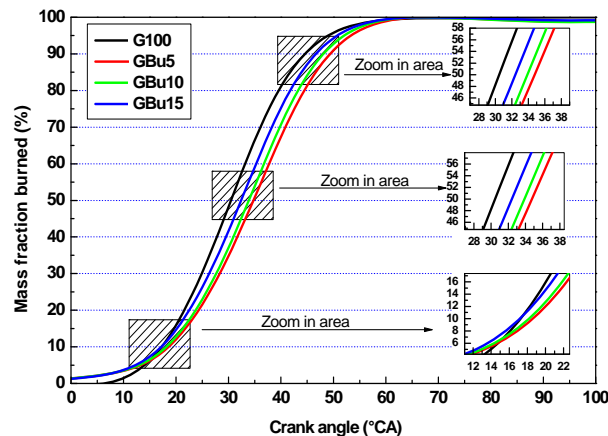

Fig. 3. Normalized mass fraction burned at 3500 RPM

Fig. 4 presents 0 – 10% MFB at 3500 RPM with 50% of WTO. The term 0 – 10% of MFB refers to early flame development of the tested fuels. Generally, blended fuels produce lower early flame development compared to G100 fuels. However with successive increases in concentration of the sec-butanol, the blended fuels early flame development tend to be shorter. Based on the calculation, the percentage differences between the blended fuels and G100 are 7.5%, 5.5% and 1.7% for GBu5, GBu10 and Gbu15 respectively. It is almost certain that lower temperature of combustible mixture would result in lower reaction rate in pre-ignition phase especially for GBu5 [29].
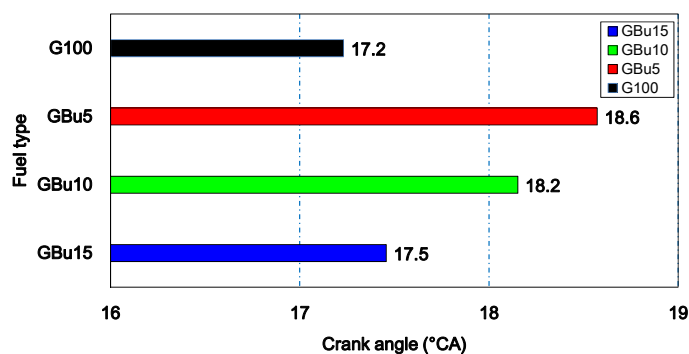
Fig. 4. 0 – 10% of MFB at 3500 RPM with 50% WTO

Fig. 5 shows 10 – 90% MFB at 3500 RPM with 50% of WTO. In the literature, the term 10 – 90% MFB was used to refer as combustion duration of the engines. In Fig. 6, it reveals that there gradual decline combustion duration with respect to butanol additions. It was also observed that a strong relationship between early flame development and combustion duration. Basically from both Fig. 4 and 5, longer flame propagation resulting in a higher combustion duration with respect to the crank angle degree positions. Comparing the results obtained between the blended and G100 fuels, GBu5, GBu10 and GBu15 experienced 9.7% 7.3% 4.5% longer combustion duration respectively. The combustion duration produced by the blended fuels is always higher as compared with that of the G100, however there a significant positive result since the trends of combustion duration decreases with addition of sec-butanol in gasoline fuels.
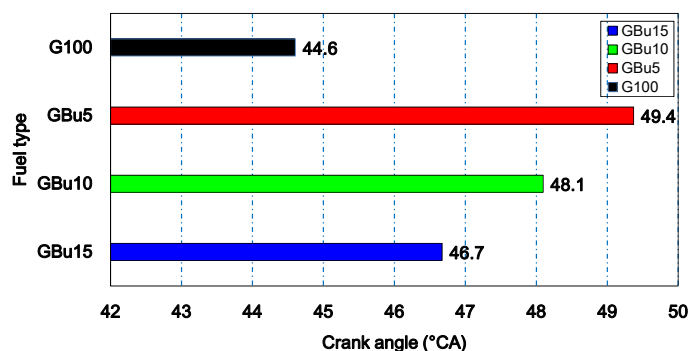

Fig. 5. 10 – 90% of MFB at 3500 RPM with 50% WTO

Fig. 6 indicates 50% position of MFB at 3500 RPM with 50% of WTO. The 50% MFB denotes the center of combustion and the engine torque strongly depends on location of 50% MFB. The location of 50% MFB of GBu15 is more advanced than that of GBu10 and GBu5, besides almost the same with G100. This is because sec-butanol produces more complete combustion due to the extra oxygen content leading to more energy input from fuel chemical reactions. Nevertheless, it was expected that if the butanol content increase more than 15%, the 50% MFB position could be equivalent to G100 fuels. With respects to G100, blended fuels produced endure reductions of 50% of MFB positions by 12.3%, 10% and 5.9% for GBu5, GBu10 and GBu15 respectively.
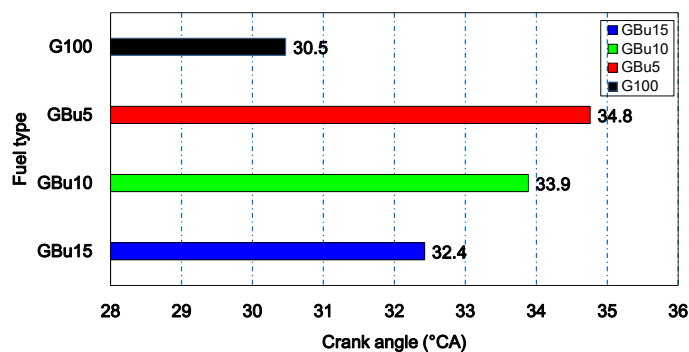

Fig. 6. 50% of MFB at 3500 RPM with 50% WTO

IV. CONCLUSION

As biofuels role is set to play an important role in future energy security utilization, the present study was designed to determine the effect of sec-butanol gasoline blends by 5%, 10% and 15%, by volume basis of sec-butanol in gasoline fuels toward its mass fraction burned characteristics particularly on 0 – 10% of MFB, 10 – 90% of MFB and 50% of MFB locations. This study has shown that all blended fuels produce lower 0 – 10% of MFB, 10 – 90% of MFB and 50% of MFB locations with respect to G100 fuels. Despite this, as the sec-butanol volume increased, the blended fuels mainly GBu10 and GBu15 exhibited shorter early flame propagation, combustion duration and 50% of MFB locations with regards to its degree of crank angle.

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