# The Investigation of a High Proportion of N-butanol Blended Fuels on Ignition Timing

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***Abstract*—The paper is to investigate the influences between the ignition timing and the high proportion of n-butanol-gasoline blends for a four-cylinder spark ignition engine. The experiment uses n-butanol-gasoline blended fuels of higher proportion (B50, B60) and pure gasoline to investigate the influence of engine performance, fuel consumption and pollutant emissions by adjusting the ignition timing and engine speed of a four-cylinder spark ignition engine. The experimental results show that the engine using n-butanol-gasoline blended fuels tends to lean air-fuel ratio and the torque output increases compared to the engine using pure gasoline. The BSFC was slightly increased at low speed, but the engine at high speed, the BSFC is decreased. CO and HC emissions can be effectively reduced, but CO2 emissions increase and that NOX emission depends on the engine operating condition. On the other hand, advancing the ignition timing which can increase the engine torque and obtain better BSFC; retarding the ignition timing which can reduce exhaust emissions of HC and NOX. Finally, the experimental results showed that the CO and CO2 was mainly influenced by λ value.**

***Index Terms*—n-butanol, Ignition timing, Blended fuel, emissions**

## I. INTRODUCTION

Biofuel has the advantages in both production and utilization, being capable of improving energy security, lowering the dependence on oil imports and reducing oil price fluctuations [1]. Biofuel is produced through an extraction technique from plants, but as the growth of plants requires absorbing carbon dioxide to perform photosynthesis, it will result in gradual reduction of carbon dioxide content on earth. Thus, using the biofuels is better than using petroleum-based fuels [2]. It is expected that by 2050, more than a quarter of the world's transportation fuels will be provided by biofuel [1].

Butanol is produced from biomass. The most productive alcohol from biomass is derived from raw material to make butanol. Literature review has stated that Jin et al. [3] conducted a study on the characteristics and applications of butanol. Butanol has more energy than ethanol. Therefore, its feature has the merits of low fuel consumption and better mileage. Dernotte et al. [4] yielded maximum reduction in HC when the proportions of n-butanol in blended fuel were attended to 40%. Ma et al. [5] used different mixing proportions of $H_2$ and CNG to a spark ignition turbocharged engine under different ignition timings. The results showed that $NO_X$, CO and HC emissions increased when one advanced the ignition timing. Huang et al. [6] presented the combustion characteristics of natural gas and hydrogen mixture on a direct-injection spark ignition engine under various ignition timing conditions and found that ignition timing had a significant impact on engine performance, combustion and emissions. Ignition timing advance will lower the concentration of HC emissions of engine and increase the concentration of $NO_X$, but there is not much difference in CO emissions under different ignition timings. Yousufuddina et al. [7] modified a single-cylinder diesel engine as a spark ignition engine and fueled it with hydrogen- ethanol dual fuel. They studied the engine performance under the conditions of fixed engine speed of 1500rpm, variable compression ratios and different ignition timings. The results showed that the maximum brake thermal efficiency and minimum brake fuel consumption value occurred at 25°of ignition timing advance. Li et al. [8] found that adjusting the injection timing and the ignition timing yield a good combustion and lower exhaust emissions, maximum heat release rate and high thermal efficiency. Turkoz et al. [9] used E85 ethanol blended fuel to a SI engine. They discovered that ignition timing advance increased the torque and caused an increase in $NO_X$ emissions, while CO and $CO_2$ remained relatively unaffected. An increase in ignition timing delay will cause poor combustion phenomenon, resulting in an increase in HC emissions and increase in fuel consumption.

Daniel et al. [10] used DMF, methanol, ethanol, butanol and other biofuels to a single-cylinder direct-injection engine and investigate the impact of ignition timing for all fuels. They found that $NO_X$ and HC of all

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fuels decreased in SR10 ignition timing. When 30% isobutanol and gasoline was mixed and used to a single-cylinder spark ignition engine by Alasfour [11], the results showed that the exhaust gas temperature increased and thermal efficiency decreased when ignition timing was delay. Xie et al [12] presented that EGR and spark timing were used to control the spark ignition of a methanol engine by varying the engine's loads. Their result indicated that the method of the high load had better performance and lower emissions than the method of the conventional throttle control. But, the fuel consumption rate, HC and CO emissions were worse at low load condition.

Topgul et al. [13] found that torque is increased and the exhaust temperature is low when unleaded gasoline-ethanol blended fuel and ignition timing advance were used by to a single-cylinder SI engine. Meanwhile, ignition timing delay can also reduce HC emissions. Gu et al. [14] investigated the various n-butanol-gasoline blends in combination with EGR in a three-cylinder, SI engine. Results showed that the EGR addition increased engine specific HC and CO emissions. Yucesu et al. [15] performed an experimental and an analysis of the mathematical modeling by adjusting the ethanol-gasoline blended fuel and the different ignition timings. They found that the blended fuels obtained a higher brake torque than using gasoline fuel when the ignition timing was delay. However, when the proportion of ethanol in blended fuel were higher, it is necessary to advance the ignition timing to get optimum torque. Sayin [16] used the different octane gasoline and different ignition timings to determine the gasoline engine performance and emissions, the results show that the high-octane gasoline can reduce brake thermal efficiency, moreover, it can also increase fuel consumption rate, and CO and HC emissions. On the other hand, increasing ignition timing will reduce BSFC, CO and HC emissions and improve BTE. Gogos et al. [17] conducted a study on the impact of ignition timing using ethanol-gasoline blended fuel, they found that ignition timing advance can increase the average pressure in the combustion chamber, thereby increasing torque and power, and reducing fuel consumption. All of the ethanol-gasoline blended fuels, E20 is able to achieve best engine performance.

From literature review, one knows that n-butanol has excellent fuel characteristics and that ignition timing has a significant impact on engine's combustion. However, a very rare research studies the n-butanol-gasoline blended fuel on a four-cylinder injection engine for perform analysis and exploration using different ignition timings and engine speeds. Hence, n-butanol-gasoline blended fuel was adopted by this paper on a four-cylinder injection engine for investigating the engine performance and exhaust pollution.

## II. EXPERIMENTAL SETUP

### A. Engine and Instrumentation

The experiments were performed on a four cylinder, four-stroke, Sentra GA16DE engine, as shown in Fig. 1. The engine was water cooled, 1597 c.c. and a compression ratio of 9.5. The schematic diagram of experimental settlement is shown in Fig. 2.

Figure 1. Experimental engine.

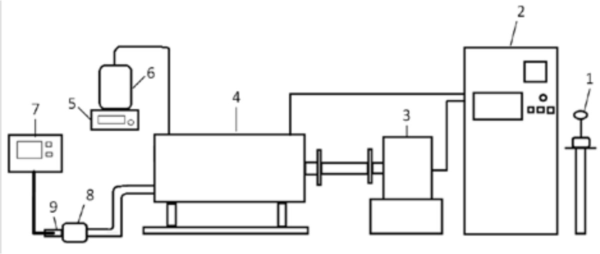

Figure 2. Schematic diagram of experimental settlement. (1. Throttle controllers 2. Dynamometer controllers 3. Dynamometer 4. Engine 5. Weighing balance 6. Fuel tank 7. Emissions analyser 8. Muffler 9. Exhaust tube).

### B. Tested Fuels

Butanol has the superior physical/chemical properties than ethanol. Properties of these fuels are shown in Table 1. In this study, 95 RON gasoline and pure n-butanol (Industrial grade, purity of 99.883%) were used as basic fuels, making three kinds of the test fuel such as pure gasoline (denoted as G), 50% n-butanol and 50% gasoline by volume (denoted as B50), 60% n-butanol and 40% gasoline by volume (denoted as B60).

TABLE I. TYPICAL PROPERTIES OF BASE FUELS [14]

| | Gasoline | Ethanol | n-Butanol |
|---|---|---|---|
| Chemical formula | C4-C12 | C2H5OH | C4H9OH |
| Composition (C, H, O) (mass%) | 86, 14, 0 | 52, 13, 35 | 65, 13.5, 21.5 |
| Lower heating value (MJ/kg) | 42.9 | 26.8 | 33.0 |
| Octane number (R + M)/2 | 95 | 100 | 89 |
| Latent heat of vaporization (kJ/kg) | 380-500 | 904 | 716 |
| Stoichiometric air/fuel ratio | 14.7 | 9.0 | 11.2 |

### C. Test Procedure

In this study, the engine is fixed at four different speeds such as 1000rpm, 2000rpm, 3000rpm, 4000rpm and 50% throttle. Five different ignition timings, 0°, 5°, 10°, 15° and 20°at BTDC were used in this paper. The temperature of cooled water was controlled and maintained at a constant degree (between 70 ± 2°C) during all the experiments. Discharged the previous tested fuel from the fuel tube before tested the next fuel. The experimental data were the average of four experimental runs. Fuel consumption was measured with a calibrated burette and a stopwatch with an accuracy of 0.1 s. The relative standard deviation of CO, CO2, O2, HC and NOX concentration was ±2%.

## III. RESULTS AND DISCUSSION

### A. *The Effect of Ignition Timing by Extra Air Ratio*

The extra air ratio is defined as follow: $\lambda =$ (the amount of air actually required) / (the amount of air theoretically required). When the engine is at low speed 1000 and 2000 rpm under 50% throttle, the status of the engine is in lean air-fuel ratio and the theoretical value λ is closed to 1. When the engine is running at high speed 3000 rpm and 4000rpm, the excess air ratio at high speed is lower than low speed. As shown in Fig. 3, when the engine is running at speed of 3000 and 4000 rpm and running at a rich air-fuel ratio, the engine has insufficient air into the combustion chamber and to cause incomplete combustion. So, an addition of n-butanol in the fuel has a direct effect on extra air ratio. From fuel characteristics, we know that the gasoline's air-fuel ratio is 14.7, and that n-butanol is 11.2. As the engine is running at air-fuel ratio of original gasoline fuel 14.7. When the engine uses n-butanol fuel, it will allow the engine to incline towards lean-burn status. The engine has more air into combustion chamber to burn the fuel. So increasing the proportion of the n-butanol in the n-butanol-gasoline blended fuel will improve the excess air ratio. Compared with pure gasoline fuel at 3000rpm, when the fuels B50 and B60 are used in the condition of the ignition timing at 15° BTDC, the excess air ratio has increased 9.41% and 11.76%, respectively, as shown in Fig. 3.

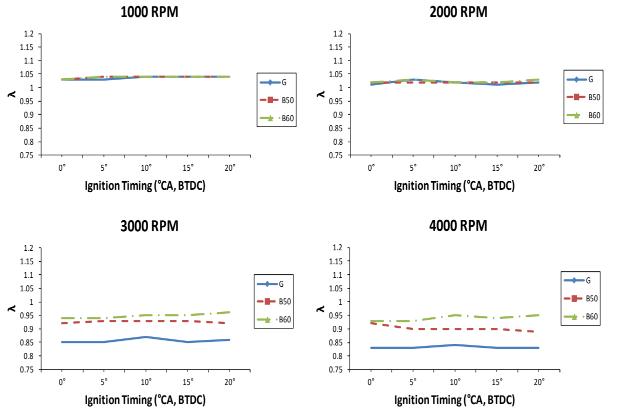

Figure 3. The effect of various ignition timings and speeds by extra air ratio.

However, when the engine at low speed 1000 and 2000 rpm, the status of the engine is in lean air-fuel ratio and the theoretical value λ is closed to 1. Hence, the fuel combustion in engine is more complete. Therefore, adding n-butanol to gasoline has no significant effect by excess air ratio. Based on experimental results, we also know that a change in engine's ignition timing has no significant variation in excess air ratio (λ) when the engine is at low speed. When the engine is running at high speed 3000 rpm and 4000rpm, the excess air ratio is lower than the engine is at low speed. Because the engine is running at high speed, the engine needs more fuel to enhance engine's power, so the excess air ratio at high speed will be lower. On the contrary, in low speed running, the leaner air-fuel ratio will result in higher excess air ratio.

### B. *The Effect of Ignition Timing on Carbon Monoxide Emissions*

As shown in Fig. 4, the concentration of CO emissions of B50 and B60 blended fuels is obviously lower than pure gasoline fuel at high engine speed 3000rpm and 4000rpm. Because the n-butanol fuel is constituted with many oxygen atoms, the extra oxygen will enhance burning effect and improve combustion during the combustion process. In addition to, from the viewpoint of the fuel characteristics, one also knows that the air-fuel ratio of n-butanol is lower than gasoline, so the engine is running at a rich air-fuel ratio at high speed. Therefore, increasing the proportion of n-butanol fuel in gasoline will relatively let the engine run at a leaner air-fuel ratio that is closed to theoretical air-fuel ratio λ = 1.0. The blended fuel can be complete combustion. The CO emissions have a significant improvement. Thus, excess air ratio (λ) has a great effect on CO emissions. When B60 fuel, ignition timing 20° BTDC and engine's speed at 3000 rpm are used to the engine test, the CO emission decreases 69.1 % compared with pure gasoline fuel. When B60 fuel, ignition timing 20° BTDC and engine's speed 4000 rpm are used to the engine test, the CO emission decreases 72.13 % compared with pure gasoline fuel, as shown in Fig. 4. In terms of ignition timing, varying ignition timing has no significant correlation on CO emissions. However, the engine's excess air ratio (λ) is still the major influential factor.

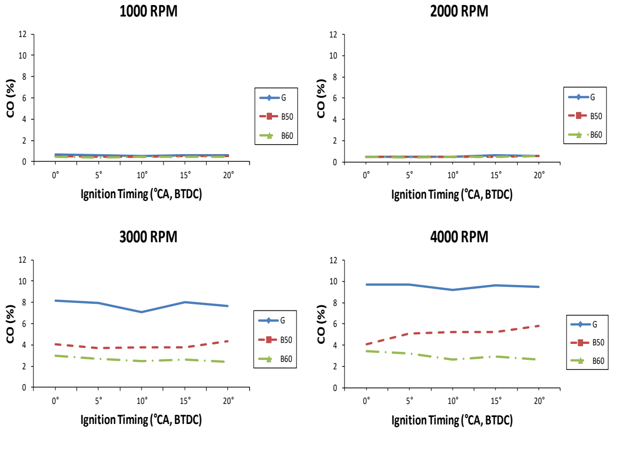

Figure 4. The effect of various ignition timings and speeds on CO emissions.

As shown in Fig. 4, the concentration of CO emissions increased as engine speed increased. This is because the engine is running at low speed 1000rpm and 2000rpm, the blended fuel into the intake port is at lean air-fuel ratio. Then, the blended fuel is more completely combustion and the concentration of CO emissions is lower than the engine is at high speed. Conversely, when the engine is running at high speed, the engine is at a rich air-fuel ratio, the concentration of CO emissions increased.

## C. *The Effect of Ignition Timing on Hydrocarbon Emissions*

The existence of oxygen atoms in n-butanol fuel will enhance more complete combustion. Add n-butanol fuel to gasoline fuel can reduce the concentration of HC emissions. When the engine is running at low speed 1000rpm and 2000rpm, the concentration of HC emissions of B60 and B50 fuels is lower than pure gasoline (G), as shown in Figure 5. Because the ignition timing of the engine is delay and the combustion phase tends to move towards the expansion stroke, all of the blended fuels on the HC emissions tend to decrease. This increases the average post-flame temperature in cylinders and exhaust temperature [10], resulting in unburned HC to promote oxidation in cylinders and the exhaust manifold. In addition, slower combustion will reduce the pressure peak value in cylinders to decrease the HC volume trapped when ignition timing is delay. On the other hand, when the engine is at the ignition timing advance, it will lead to the combustion process occurred earlier and reduced the post-flame temperature in cylinders and exhaust temperature. Therefore, the concentration of HC emissions is increased.

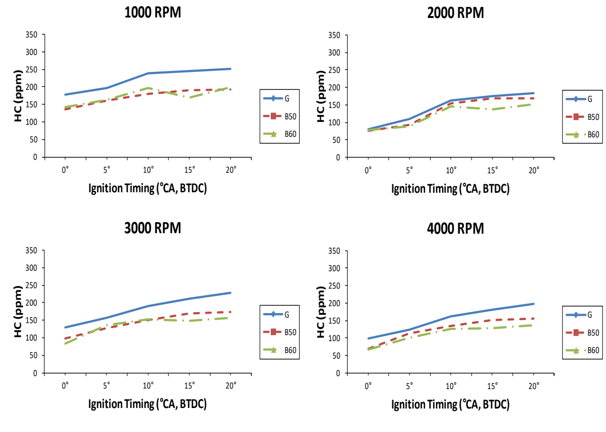

Figure 5. The effect of various ignition timings and speeds on HC emissions.

At a higher engine speed, the air mass flow rate in intake is low. The engine's cylinder pressure is reduced during combustion process. This reduces the amount of unburned combustion mixture to escape from the gap of combustion chamber during the combustion process and the HC emission is reduced. In addition, the lower cylinder pressure and shorter engine combustion cycle at a higher engine speed reduce the absorption/desorption process of fuel on the oil film of cylinders, which also helps to reduce HC emissions. Therefore, the concentration of HC emissions at high engine speed is lower than the low engine speed [18].

## D. *The Effect of Ignition Timing on Carbon Dioxide Emissions*

The relationship between the concentration of $CO_2$ emission and the CO emission is inversely each other. As shown in Fig. 6, the $CO_2$ emissions of B50 and B60 blended fuels are higher than pure gasoline. This is due to the existence of oxygen atoms in n-butanol itself, and has extra oxygen to burn the fuel completely and increase $CO_2$ emissions. In addition, when the engine is running at the gasoline's air-fuel ratio mode 14.7:1, the blended fuel including 50% or 60% n-butanol, the engine tends to run at lean-burn status because the air-fuel ration of n-butanol is 11.2:1. The engine is running under a lean air-fuel ratio. There is enough air to make fuel burn completely, so the concentration of $CO_2$ emission increases. Obviously, when the blended fuels B50 and B60 are used to engine test at ignition timing 20° BTDC and engine speed 4000rpm, the $CO_2$ increases 21.67% and 40.1%, respectively, compared to pure gasoline fuel.

At low engine speed, the blended fuel slightly increase $CO_2$ emission, but the rate of increase is not big. This is because the engine's excess air ratio is closer to 1 under low engine speed. Varying ignition timing has not dramatic effect on $CO_2$ emissions when the blended fuel B50 and B60 and pure gasoline (G) are used to test engine.

At low engine speed, the engine's fuel supply mode is in lean air-fuel status and the $\lambda$ value is closer to 1, so the combustion is more complete. Conversely, at high engine speed, the engine's fuel supply mode is at rich air-fuel status. In this status, air is not sufficient supplied to enhance engine's complete fuel combustion. Therefore, the concentration of $CO_2$ emissions is higher when the engine is running at low speed.

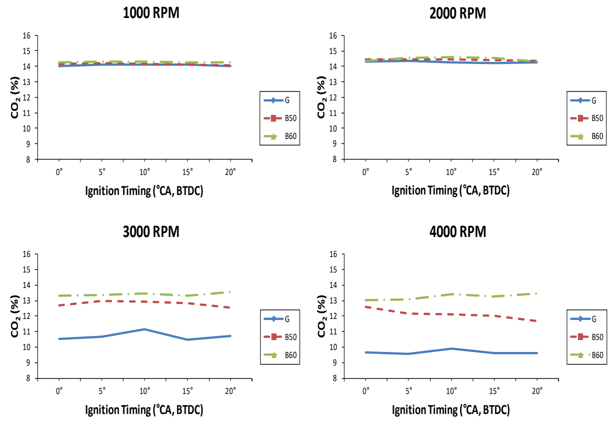

Figure 6. The effect of varying ignition timings and speeds on $CO_2$ emissions.

## E. *The Effect of Ignition Timing on Nitrogen Oxide Emissions*

As shown in Fig. 7, the concentration of $NO_X$ emission for the engine using blended fuels has not dramatic effect compared to pure gasoline when the engine is running at low speed 1000rpm and 2000rpm. But, the concentration of $NO_X$ emissions of n-butanol-gasoline blended fuel B50 and B60 is slightly lower than pure gasoline (G). The reason is that the latent heat of vaporization of n-butanol is higher than gasoline. Therefore, using n-butanol-gasoline blended fuel reduces the temperature of intake air and cause the maximum combustion temperature to drop slightly. The maximum combustion temperature drops, resulting in decreased concentration of $NO_X$ emissions.

At high engine speed 3000rpm and 4000rpm, the concentration of $NO_X$ emissions of the blended fuels B60 and B50 is higher than pure gasoline (G). This is because increasing the proportion of n-butanol in the blended fuel let the λ value of blended fuel be close to 1, the combustion process of the blended fuel towards the lean-burn status and the air is enough to do a complete combustion. At this moment, increasing the temperature of cylinders lets the concentration of $NO_X$ emissions increase. The advance of the ignition timing increases the maximum cylinder peak pressure and the maximum temperature of cylinders resulting in the increase of the $NO_X$ emissions. The delay of the ignition timing decreases $NO_X$ emissions due to slow combustion speed, and a drop in maximum cylinder pressure and combustion temperature in cylinders, resulting in the reduction of the concentration of $NO_X$ emissions. Hence, varying the engine's ignition timing has a significant direct effect on $NO_X$ emissions. The use of the blended fuels B50 and B60 at the ignition timing BTDC 0°and the engine speed 3000 rpm, $NO_X$ emission would increase 93.86 % and 307.9 %, respectively. Similarly, $NO_X$ emission would increase 262.64 % and 285.71 % at the engine speed 4000rpm and the ignition timing BTDC 0° when the blended fuels B50 and B60 are used.

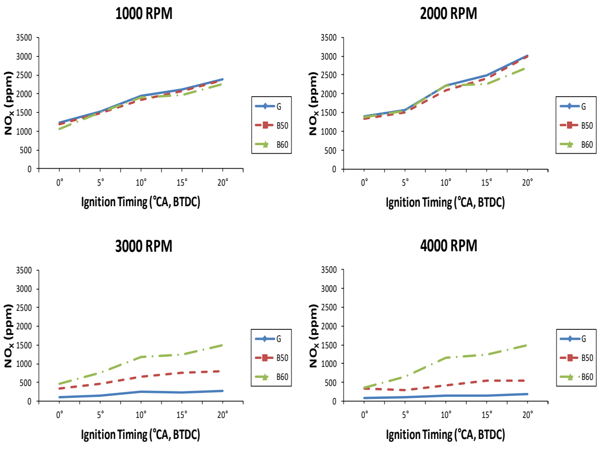

Figure 7. The effect of various ignition timings and speeds on $NO_X$ emissions.

### F. The Effect of Ignition Timing on Engine Torque Output

The latent heat of vaporization of n-butanol is higher than gasoline. This lets the temperature of the air intake manifold decrease and the air mass density of the air intake increase. Therefore, the volumetric efficiency was improved resulting in the engine's torque output of B50 and B60 blended fuels is slightly higher than pure gasoline, as shown in Fig. 8 at 4000rpm. Furthermore, the air-fuel ratio of n-butanol is lower than pure gasoline. The proportion of n-butanol added to gasoline increase the excess air ratio (λ) is to create a lean-burn effect such that the combustion is close to chemometrics air-fuel ratio. The engine yields better combustion and increases engine torque. When the blended fuels B50 and B60 are used to engine test under the ignition timing condition of 0° BTDC and 4000rpm, the engine torque output has increased 7.96% and 7.09%, respectively, compared to pure gasoline fuel. However, the excess air ratio λ is larger than 1 at low engine speed 1000rpm, as shown in Fig. 8. Add the n-butanol fuel to gasoline do not change the combustion condition. Therefore, the torque output of the engine is insignificant difference using any fuels.

The delay off the ignition time reduces he engine torque output due to large amounts of post-combustion of fuel at TDC during the combustion process, resulting in incomplete combustion and the reduction of the engine torque output. On the contrary, the advance of the ignition time lets the combustion process be close to TDC such that the blended fuels has enough time to burn, resulting in the improvement of the engine's thermal efficiency and the increase of the engine torque output. The engine torque output increases with increasing the engine speed.

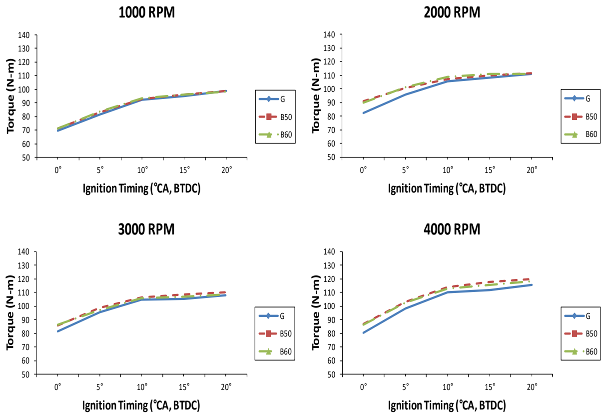

Figure 8. The effect of various ignition timings and speeds on engine torque.

### G. The Effect of Ignition Timing on Brake Specific Fuel Consumption (BSFC)

The engine is running at low speed 1000 rpm and 2000 rpm. Increasing the proportion of butanol fuel in the led to increased fuel consumption, as shown in Fig. 9. This is because the heating value of n-butanol is lower than pure gasoline. Therefore, if the blended fuel is to produce the same power output, an extra fuel must be supplied. The results show that the BSFC of the blended fuels B50 and B60 at the engine speed 1000rpm and the ignition time BTDC 0° increase 15.4 % and 17.72 % compared to pure gasoline. Similarly, at the engine speed 2000 rpm and the ignition time BTDC 0°, the BSFC of the blended fuels

B50 and B60 increases 11.26 % and 13.38 % compared to pure gasoline.

An increase in the proportion of n-butanol fuel, the fuel consumption BSFC is reduced when the engine test is at the engine speed 3000 rpm and 4000 rpm and each ignition time. The reason is that during high speed running, the engine is running at a rich fuel status. An increase in added proportion of n-butanol will allow combustion to incline towards lean-burn status to improve combustion efficiency and reduce fuel consumption. When the blended fuels B50 and B60 are used to engine test under the ignition timing condition of 5 ° BTDC and 4000rpm, the BSFC has decreased 11.51% and 15.7%, respectively as compared with pure gasoline fuel.

The experimental result shows that the advance of the ignition time is able to yield better fuel consumption and power performance, as shown in Fig. 9. Because the advance of the ignition time can allow the fuel to have sufficient time to burn completely before TDC and allow the pressure and temperature of interior cylinders to increase and achieve better power performance, fuel consumption is reduced. On the contrary, the delay of the ignition time will allow the combustion process to take place after TDC, resulting in loss of engine power and the increase of the fuel consumption.

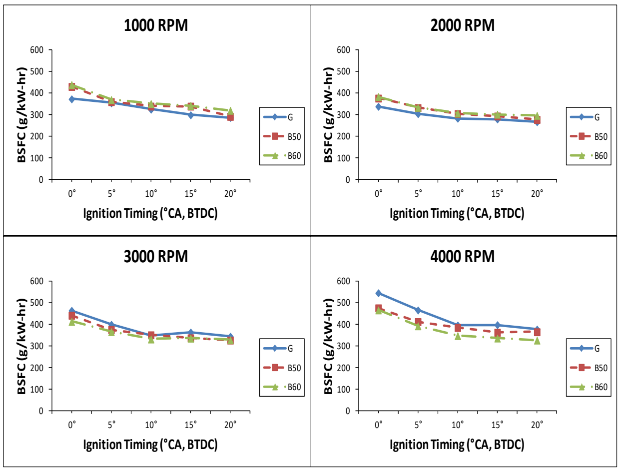

Figure 9. The effect of various ignition timings and speeds on BSFC.

## IV. CONCLUSION

1) An increase in added proportion of n-butanol in fuel will tend to allow the engine to incline towards lean-burn status and to increase the excess air ratio.
2) Using a higher proportion of n-butanol-gasoline blended fuel increases engine torque. The ignition timing advance causes an increase in the engine's torque; the ignition timing delay causes the reduction of the engine torque. If the engine uses B50 blended fuel and adjusts the ignition timing at BTDC 0 and is running at 2000 rpm, the engine torque is increased up to about 10.45%.
3) The use of n-butanol-gasoline blended fuel in engine at low speed running and at any ignition timings will tend to increase BSFC compared to pure gasoline. However, the fuel consumption of the BSFC is lower than pure gasoline when the engine is running at high speed. The ignition timing advance obtains a lower BSFC. The ignition timing delay gets a higher SFC.
4) The use of n-butanol-gasoline blended fuel can reduce the values of the CO and HC emissions. Moreover, because the blended fuels combustion is complete, it will cause the concentration of $CO_2$ emissions to increase. If a higher proportion of n-butanol-gasoline blended fuel is used to low engine speed, $NO_X$ emissions will tend to decrease slightly due to the property of the blended fuel.
5) Raising the engine speed, the CO emissions and the engine torque are increased and the concentration of the HC, $CO_2$ and $NO_X$ emissions and the excess air ratio are decreased. Meanwhile, the best BSFC can be achieved at 2000rpm.
6) Varying ignition timing has no significant effect on excess air ratio, CO and $CO_2$ emissions. The prime influential factors lie in the amount of air during combustion and the concentration of engine's fuel supply at that instance.

In conclusion, Ignition timing advance will enhance torque, but HC and $NO_X$ emissions will increase. Ignition timing delay will decrease HC and $NO_X$ emissions, but the torque will decrease.

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