# Investigation of N-Butanol Blending with Gasoline using a 1-D Engine Model

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Abstract: Increasing demand and limited reserves for fossil fuel together with carbon emissions regulations have led to producing sustainable fuels made from renewable materials. In recent years, the focus has been on using bio-fuels as alternate energy sources. Blending bio-fuels with gasoline is one of the methods to be considered under the search for a new source of energy. Alcohols are an important category of bio-fuels. Butanol can be an alternative fuel since it is a liquid and has several physical and chemical properties similar to those of gasoline fuels. Butanol don't have many of the drawback associated with ethanol. Butanol has also a higher molecular weight than ethanol, and therefore, has reduced vapour pressure, lower water solubility, and higher energy density. That is why this study is aimed to develop the 1-D model of a PFI (Port Fuel Injection) engine for predicting the effect of various blends of butanol and gasoline on engine performances and fuel consumption. AVL Boost was used as a simulation tool to analyze the performance and emissions for different blends of n-butanol and gasoline by volume (n-B0, n-B5, n-B10, n-B20, n-B30, n-B50 and n-B85).

## 1 INTRODUCTION

Ethanol, butanol and biodiesel are main biofuels. Butanol (butyl alcohol) is a liquid alcohol fuel and can work in the internal combustion engine with gasoline without any modification. It can be produced from biomass (biobutanol) or from fossil fuels (petrobutanol). Both alcohols biobutanol and petrobutanol have the same chemical properties. The energy density of butanol is closer to gasoline than the other alternative additives as ethanol and methanol which are commonly used today. Butanol is less hygroscopic so it does not require the different handling that ethanol and methanol required. Also, it means that Butanol is less corrosive than ethanol and methanol. In comparison to ethanol, butanol is less prone to water contamination. As a result it could be distributed using the same infrastructure used to transport gasoline. Butanol can burn at a wider range of temperatures than ethanol, and has better cold start properties. Many investigations lead to conclusion that that it can be used alone or can be mixed with gasoline in an internal combustion engine (ICE). Furthermore, butanol has a high enough octane number, close to that of gasoline and a lower vapor pressure. The higher octane number, the more compression the fuel can withstand before detonating. Premature fuel ignition can damage engine, which is a common phenomenon for lower octane number fuel. These properties make it more suitable additive than ethanol and methanol for gasoline fuel.

There are four butyl alcohols with the same chemical composition consisting of 4 carbon atoms, 10 hydrogens and 1 oxygen and they have identical chemical pattern $C_4H_{10}O$, but they differ each from others with respect to their structure (Szwajaa and Naber, 2010). The chemical nature of alcohols are as follows:

- 1-butanol (n-butanol, n-butylalcohol) $CH_3\,(CH_2)_2\,CH_2\,OH$,
- 2-butanol $CH_3CH(OH)CH_2CH_3$,
- 3-butanol $(CH_3)_3COH$,
- iso-butanol $CH_3(CH_2)_3OH$.

The common fuel properties of n-butanol in comparison to gasoline and other alcohol fuels are given in Table 1 (Yacoub, Bara and Gautam 2000), (Gautam and Martin, 2000). Form this table, it can be said that about the latent heat of vaporization of these fuels, butanol is less attractive than others. For PFI (port fuel injection) systems, fuels with higher latent heat of vaporization have larger decreases in temperature of intake charge with complete



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Table 1: Properties of several fuels (Yacoub, Bara and Gautam 2000), (Gautam and Martin, 2000).

| Fuel | Chemical formula | Specific gravity ($kg/dm^3$) | Lower heating value (MJ/kg) | Stoichiometric air–fuel ratio ($kg_{air}/kg_{fuel}$) | Energy density of a stoichiometric air–fuel mixture (MJ/kg) | Latent heat of vaporization (at boiling point) (kJ/kg) | Octane number (RON+MON)/2 |
|---|---|---|---|---|---|---|---|
| Methanol | $CH_3OH$ | 0,7913 | 20,08 | 6,43 | 2,750 | 1098 | 99 |
| Ethanol | $C_2H_5OH$ | 0,7894 | 26,83 | 8,94 | 2,699 | 838 | 100 |
| n-Butanol | $C_4H_9OH$ | 0,8097 | 32,01 | 11,12 | 2,641 | 584 | 86 |
| Gasoline | $C_8H_{15}$ | 0,7430 | 42,9 | 14,51 | 2,769 | 349 | 87 |

vaporization in the intake port. To match the combustion characteristics of gasoline, the utilization of butanol fuel as a substitute for gasoline requires fuel-flow increases (though butanol has only slightly less energy than gasoline, so the fuel-flow increase required is only minimal, maybe 10%). Higher oxygen content and lower octane number of n-butanol need changes in initial engine calibration, determined with pure gasoline. Also butanol has a higher laminar flame propagation speed than gasoline, which makes combustion process finish earlier and improving the engine thermal efficiency.

Since using blended alcohol-gasoline fuels can reduce the air pollution, many researchers have studied the effect of these alcohol blended fuels on the performance and exhaust emission of a spark-ignited engine. In a study conducted by (Alasfour, 1998), NOx emissions were presented as a function of air/fuel equivalence ratio. It is showed decreasing in NOx emissions when a 30% butanol-gasoline blend was used. Peak NOx emissions were received at a slightly leaner mixture for a 30% butanol–gasoline blend than for pure gasoline.

Switching a gasoline engine over to butanol would in theory result in a fuel consumption penalty of about 10% but there is no scientific study yet which butanol effects on fuel consumption for the commercial vehicles. While the energy density for any mixture of gasoline and butanol can be calculated, tests with other alcohol fuels have demonstrated that the effect on fuel economy is not proportional to the change in energy density (Minter, 2006).

There are many investigations on butanol utilization in gasoline engines. The researchers (Wallner, Miers and McConnell, 2009; Rakopoulos, Papagiannakis and Kyritsis, 2011; Sarathy *et al.*, 2009) investigated the unburned hydrocarbon (HC), carbon monoxide (CO) and nitrogen oxides (NOx) emissions with gasoline, 10% ethanol and 10% n-butanol blends in a direct injection spark-ignition engine. Their results showed little difference in HC, CO and NOx emissions between gasoline and 10% n-butanol. The reason for this is the engine is operated at the stoichiometric air/fuel ratio for each specific fuel blend. The researchers (Dernotte, *et al.*, 2010) examined the emissions characteristics of several n-butanol–gasoline blends (0, 20, 40, 60 and 80 vol. % of n-butanol in gasoline) using a PFI spark-ignition engine and found that n-butanol (B60) and n-butanol (B80) produced 18% and 47% more unburned HC emissions than neat gasoline, respectively. It was found that B80 was the only n-butanol blended fuel, which it did not produce lower CO emissions than neat gasoline.

Other researchers (Gu X *et al.*, 2012) tested five gasoline butanol blendes (B0, B10, B30, B40 and B100) and results showed that the unburned HC and CO emissions of blends are lower than those of gasoline. Pure n-butanol (B100) increases the unburned HC and CO emissions compared to those of gasoline. They also showed that the addition of n-butanol decreased the particle emissions. In another study (Feng *et al.*, 2013) for pure gasoline and 35% by volume butanol-gasoline blend. The results showed that engine torque, brake specific fuel consumption (BSFC) and CO and HC emissions were better than those of pure gasoline at both full load and partial load with 35% volume butanol addition. But $CO_2$ emission was worse than that of the original level of pure gasoline.

There are many studies focused on conventional harmful exhaust emissions (CO, HC and NOx) when use butanol as spark ignition engine fuel. Although $CO_2$ is a non-toxic gas, which is not classified as an engine pollutant, it is one of the substances responsible for global temperature rises through the greenhouse effect. $CO_2$ emission has not been usually taken into account in many studies. (Emilio *et al.*, 2013; Ritche *et al.*, 2012).

The objective of this paper is to investigate CO, HC, NOx, BSFC, power and torque for various n-butanol-gasoline blends at diferent engine speed.

## 2 METODOLOGY

Engine simulation is becoming an increasingly important engineering tool for time and cost efficiency in the development of internal combustion engines (ICEs). Most of results that are obtained by simulation are rather difficult to be obtained experimentally. The use of Computational Fluid Dynamics (CFD) simulations allow researchers to understand flow behaviour and quantify important flow parameters such as mass flow rates or pressure drops, provided that the CFD tools have been properly validated against experimental results. For reasons such as the aforementioned, CFD simulations have become a valuable tool in helping both the analysis and design of the intake and exhaust systems of an ICEs. Many processes in the engine are 3-D but it requires greater knowledge and large computational time. Thus simplified 1-D simulation is often used. There are several components that manifest a complex three-dimensional flow behaviour, such as turbo machinery or manifolds which cannot be simulated properly by 1-D codes, and thus require viscous, 3-D codes (Iliev S. 2015).

The present paper aims to develop the 1-D simulation model of four-stroke port fuel injection (PFI) gasoline engine for predicting the effect of n-butanol–gasoline (n-B0, n-B5, n-B10, n-B20, n-B30, n-B50 and n-B85) fuel blends on the performance and emissions of SI engine. For this purpose, the simulation of a calibrated gasoline engine model was used as basic operating condition, and the laminar burning velocity correlations of n-butanol–gasoline fuel blends was considered for calculating the different combustion duration. The engine performances: torque and specific fuel consumption were compared and discussed.

### 2.1 Simulation Setup

The 1-D engine simulation model is developed by using the software AVL BOOST and has been employed to study the engine performance working on n-butanol-gasoline blends.

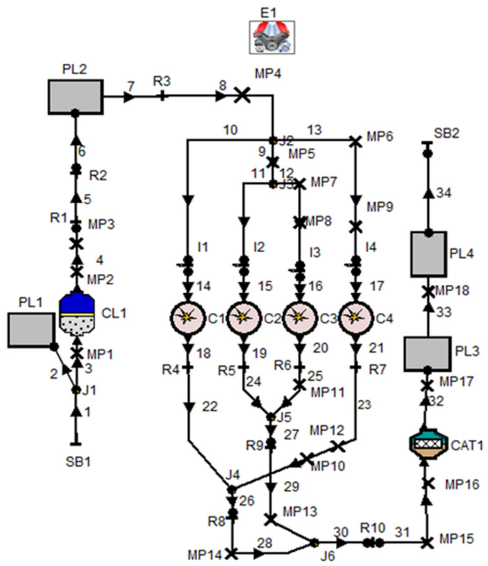


Figure 1: Layout of engine model.

The pre-processing step of AVL Boost enable the user to model a 1-Dimensional (1-D) engine test bench setup using the predefined elements provided in the software toolbox. The various elements are joined by the desired connectors to establish the complete engine model using pipelines.

Table 2: Engine specification.

| Engine parameters | Value |
|---|---|
| Bore | 86 (mm) |
| Stroke | 86 (mm) |
| Compression ratio | 10,5 |
| Connection rod length | 143,5 (mm) |
| Number of cylinder | 4 |
| Piston pin offset | 0 (mm) |
| Displacement | 2000 (cc) |
| Intake valve open | 20 BTDC (deg) |
| Intake valve close | 70 ABDC (deg) |
| Exhaust valve open | 50 BBDC (deg) |
| Exhaust valve close | 30 ATDC (deg) |
| Piston surface area | 5809 ($mm^2$) |
| Cylinder surface area | 7550 ($mm^2$) |
| Number of stroke | 4 |

In Fig.1, E1 represent the engine while C1, C2, C3 and C4 represent the number of cylinders of the engine. MP1 to MP18 represent the measuring points. PL1, PL2, PL3 and PL4 represent the plenum. SB1 and SB2 are for the system boundary. The flow pipes are numbered 1 to 34. CL1 represent the cleaner. R1 to R10 represent flow restrictions, CAT1 represent catalyst and I1 to I4 represent fuel injectors.

The engine model used in this simulation was performed on a four stroke, four cylinder spark ignition engine with port fuel injection. The gasoline engine model was calibrated and described by (Iliev S. 2014) and its layout is shown in Fig. 1 with engine specification shown in Table 1.

# 3 RESULT AND DISCUSSON

The present study concentrated on the emission and performance characteristics of the n-butanol-gasoline blends. Different concentrations of the blends 0% n-Butanol (n-B0), 5% n-Butanol (n-B5), 10% n-Butanol (n-B10), 20% n-Butanol (n-B20), 30% n-Butanol (n-B30), 50% n-Butanol (n-B50) and 85% n-Butanol (n-B85) by volume were analyzed using AVL BOOST at full load conditions for the speeds ranging from 1000 - 6500 rpm in the steps of 500rpm. The results are divided into different subsections based on the parameter analyzed.

## 3.1 Engine Performance Characteristics

The results of the brake power, and specific fuel consumption for n-Butanol gasoline blended fuels at different engine speeds are presented here.

Fig. 2 shows the influence of n-Butanol gasoline blended fuels on engine brake power.

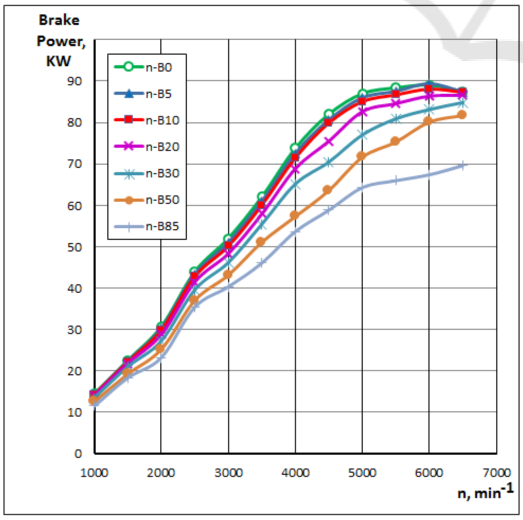


Figure 2: Influence of n-Butanol gasoline blended fuels on engine brake power.

The brake power is one of the important factors that determine the performance of an engine. The variation of brake power with speed was obtained at full load conditions for n-B5, n-B10, n-B20, n-B30, n-B50 and pure gasoline n-B0, using the CFD results.

When the n-Butanol content in the blended fuel was increased, the engine brake power decreased for all engine speeds. The brake power of gasoline was higher than those of n-B5 to n-B85 for all engine speeds. The heating value of n-Butanol is lower than that of gasoline and heating value of the blended fuel decreases with the increase of the n-Butanol content. As a result, a lower power output is obtained.

Butanol addition to the gasoline does not affect engine power significantly, but especially at high engine speed (over 4000 $min^{-1}$) there is a sharp reduction the power curves compared to pure gasoline (Fig. 2). The reason of this reduction can be affected by the low calorific value of butanol.

This may refer to some reasons as follows. Combustion characteristic of n-butanol is different from gasoline since the latent heat of n-butanol is higher than that for gasoline (584 kJ/kg, 349 kJ/kg for n-butanol and gasoline, respectively). This means that the n-butanol absorbs more heat in order to evaporate and burn.

Fig. 3 shows the influence of n-Butanol gasoline blended fuels on engine torque. The increase of n-Butanol content (n-B5 – n-B85) decreased the torque of the engine. The brake torque of gasoline was higher than those of n-B5-nB85.

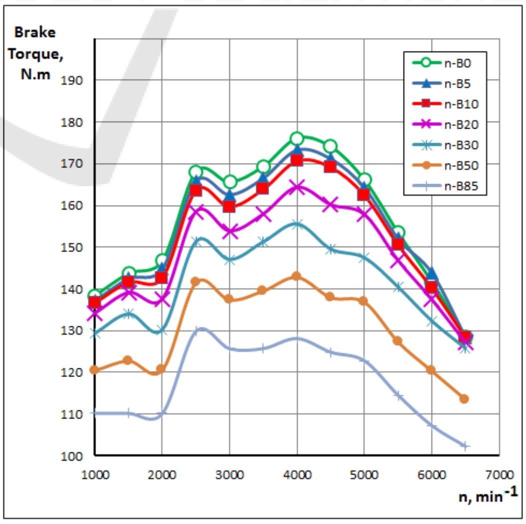


Figure 3: Influence of n-Butanol gasoline blended fuels on engine torque.

The calorific value of butanol is lower than the calorific value of gasoline, therefore it is expected that any butanol addition to the gasoline reduces the torque output of the engine. However oxygen content of butanol improves the combustion in the cylinder and with the 5% and %10 butanol blends similar value are achieved with gasoline. On the other hand, because of the existence of oxygen in the butanol chemical component, and the increase of n-Butanol, lean mixtures are produced that decrease equivalence air-fuel ratio to a lower value and due to the presence of oxygen which has entered the combustion chamber makes the burning more efficient.

Regarding the stumpy of volumetric efficiency of blended fuels, it is mainly due to the low saturation pressure of n-butanol compared to gasoline fuel (2.27 kPa of n-butanol and 31 kPa for gasoline); the saturation pressure is strongly linked to the ability of the fuel to vaporize. The lower the saturation pressure is, the ability of the fuel to evaporation is increased. When fuel is evaporated, the volume of vaporized fuel will displace some incoming air, e.g., less air. Besides, fuels with a smaller stoichiometric air–fuel ratio, like n-butanol 11.2, have a lower volumetric efficiency. But, n-butanol has high heat of vaporization, so some volumetric efficiency lost due to air-fuel ratio and saturation pressure is partially gained back again. Besides, it is possible to improve the volumetric efficiency of n-butanol by cooling the air and fuel before accessing onto the engine system. In addition, manifolds with late fuel addition and wider runners can be designed to further increase the volumetric efficiency.

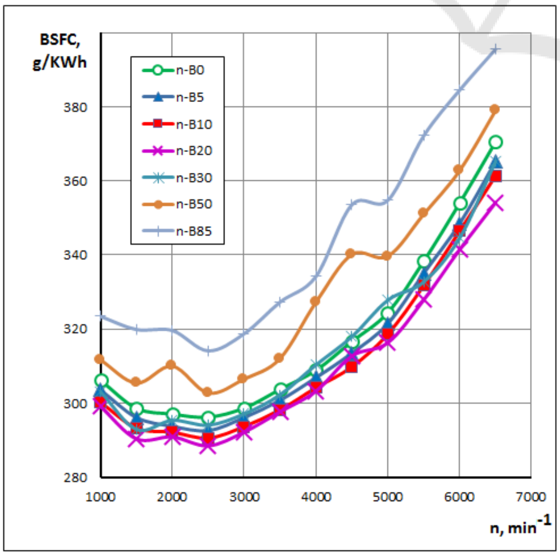


Figure 4: Influence of n-Butanol gasoline blended fuels on brake specific fuel consumption.

Fig. 4 indicates the variations of the BSFC for n-Butanol gasoline blended fuels under various engine speeds. As shown in this figure, the BSFC increased as the n-Butanol percentage increased. The well-known reason, that the lower heating value and stoichiometric air-fuel ratio for this fuel leads that for specific air-fuel equivalence ratio, more fuel is needed. The highest specific fuel consumption is obtained for n-B85 blended fuel. Also, a slight difference exists between the BSFC when using gasoline and when using n-Butanol gasoline blended fuels (n-B5, n-B10 and n-B20). The lower energy content of butanol gasoline blended fuels causes some increment in BSFC of the engine when it is used without any modification.

## 3.2 Engine Emissions Characteristics

Fuels consist of Hydrogen (H) and Carbon (C) molecules. During the combustion period in the engine cylinder, these C and H molecules react with oxygen (O2) in the air and converted to the CO, CO2, HC. These exhaust tail emissions are harmful for human health and environmental pollution. Carbon monoxide (CO) is colorless, odorless, tasteless gas which is lighter than air. It is highly toxic to humans and animals in higher quantities. CO is a common industrial hazard resulting from the incomplete burning of natural gas and any other material containing carbon.

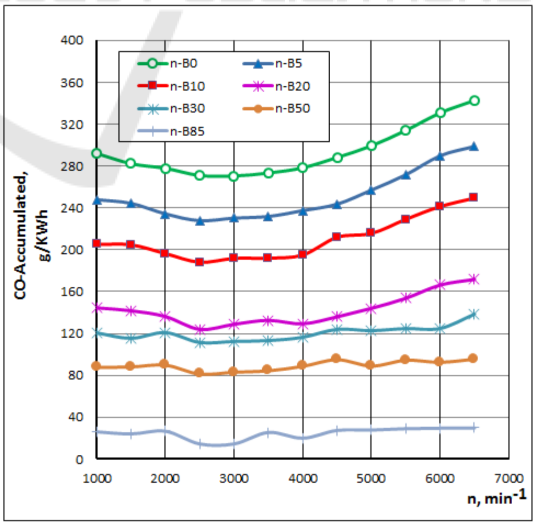


Figure 5: Influence of n-Butanol gasoline blended fuels on CO emissions.

The effect of the n-Butanol gasoline blends on CO emissions for different engine speeds is shown in Fig. 5. It can be seen that when n-Butanol percentage increases, the CO concentration decreases. This can be explained by the enrichment of oxygen owing to the n-Butanol, in which an increase in the proportion of oxygen will promote the further oxidation of CO during the engine exhaust process. Another significant reason for this reduction is that n-Butanol ($C_4H_9OH$) has less carbon than gasoline ($C_8H_{15}$). The lowest CO emissions are obtained with blended fuel containing n-Butanol (n-B95).

When using gasoline as fuel in a spark ignition engine, the unburned fuel hydrocarbons (HC) in the exhaust consist mainly of unburned gasoline which itself largely consists of hydrocarbons. However, when using gasoline-Butanol blends as fuel the un-combusted fuel constituents include both unburned gasoline (which consists mainly of hydrocarbons as noted) and un-combusted Butanol. Thus, the HC emissions measured in the diluted exhaust consist of both hydrocarbons and Butanol. From a legal perspective, HC emissions are regulated by law, but not Butanol emissions. This means that reported HC emissions from vehicles fueled with alcohol-gasoline blends are overestimated, due to the contribution of the alcohol contents in the exhaust emitted from the vehicle, and the larger the alcohol contents present in the exhaust, the greater the error in estimated HC emissions (Egeback *et al.*, 2005).

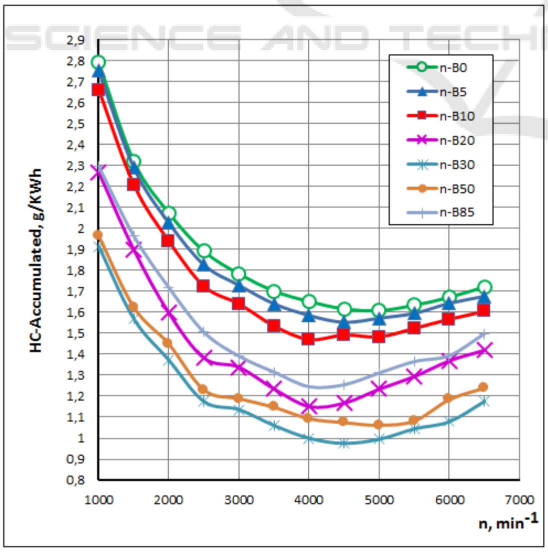


Figure 6: Influence of n-Butanol gasoline blended fuels on HC emissions.

The effect of the n-Butanol gasoline blends on HC emissions for different engine speeds is shown in Fig. 6. It can be seen that when n-Butanol percentage increases, the HC concentration decreases. The concentration of HC emissions decreases with the increase of the relative air-fuel ratio. The reason for the decrease of HC concentration is similar to that of CO concentration described above.

Nitrogen oxides (NO and $NO_2$) are formed by the oxidation of nitrogen from the air in the combustion process. An important parameter for the formation of nitrogen oxides is the combustion temperature (increased combustion temperature results in increased nitrogen oxide emissions). Therefore, its probable formation is in very high temperature regions, which are related to heat release (Raslavicius L. 2010). It should be noted that nitrogen oxides ($NO_X$) are regulated pollutants that are determined jointly, as the sum of NO and $NO_2$ contents rather than as individual components (Egeback *et al.*, 2005).

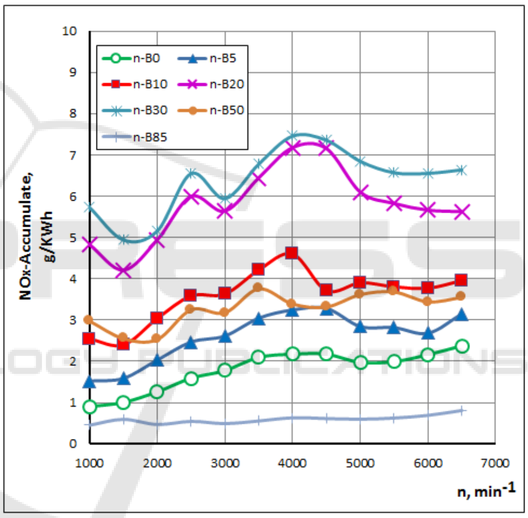


Figure 7: Influence of n-Butanol gasoline blended fuels on NOx emissions.

The effect of the n-Butanol gasoline blends on NOx emissions for different engine speeds is shown in Fig. 7. It can be seen that when n-Butanol percentage increases up to 50% n-B50, the NOx concentration increase after which it decreased with increasing n-Butanol percentage. This can be explained by that improved combustion inside the cylinder resulting in an increased in-cylinder temperature. The higher percentage of n-Butanol in gasoline reduces the in-cylinder temperature. The reasons for the reduction in temperature are: 1. Latent heat of evaporation of n-Butanol, which decreases the in-cylinder temperature when they vaporizes, 2. There are more triatomic molecules are produced, the higher the gas heat capacity and the lower the combustion gas temperature will be. However the low in-cylinder temperature can also lead to an increment in the unburned combustion product.

## 4 CONCLUSIONS

The present paper demonstrates the influences of n-Butanol addition to gasoline on SI engine performance and emission characteristics. General results concluded from this study can be summarized as follows:

- When the n-Butanol content in the blended fuel was increased, the engine brake power decreased for all engine speeds. The engine performance of blends is lower than gasoline due to the combustion characteristics of n-butanol (higher latent heat and lower calorific value than gasoline). The lower saturation pressure of n-butanol compared to gasoline leads to a lower volumetric efficiency for blended fuels. The engine performance of blends could be improved by modifying ignition time and increasing compression ratio since n-butanol has more resistance to detonation than gasoline.
- The BSFC increased as the butanol percentage increased. Also, a slight difference exists between the BSFC when using gasoline and when using gasoline blended fuels n-B5, n-B10, n-B20 and n-B30.
- When n-Butanol percentage increases, the CO and HC concentration decreases.
- Butanol gasoline blends the significant increase NOx emissions with the increase of butanol percentage. When butanol percentage increases up to 50% n-B50, the NOx concentration increase after which it decreased with increasing butanol percentage.

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## REFERENCES

Szwajaa, S., Naber, J.D., 2010. Combustion of n-Butanol in a Spark Ignition IC Engine, *Fuel*, Vol. 89, Isuse 7, pp.1573-1582.

Yacoub, Y., Bara, R., Gautam, M., 1998. The performance and emission characteristics of C1–C5 alcohol–gasoline blends with matched oxygen content in a singlecylinder spark ignition engine. Proc Inst Mech Eng A – *Power Energy*; 212:363–79.

Gautam, M., Martin, DW., 2000. Combustion characteristics of higher-alcohol/gasoline blends. *Proc Inst Mech Eng*; 214A:497–511.

Alasfour F.N., 1998. NOx emission from a spark-ignition engine using 30% iso-butanol - gasoline blend: Part 1: Preheating inlet air, *Appl. Therm. Eng*. 18, 5, p. 245-56.

Minter, S., 2006. Alcoholic Fuels, Taylor&Francis Group, 270 pages.

Wallner T, Miers SA, McConnell S., 2009. A comparison of ethanol and butanol as oxygenates using a direct-injection, spark-ignition engine. J Eng Gas Turbines Power; 032802:9.

Rakopoulos DC, Rakopoulos CD, Papagiannakis RG, Kyritsis DC, 2011. Combustion heat release analysis of ethanol or n-butanol diesel fuel blends in heavy-duty DI diesel engine. Fuel; 90:1855–67.

Sarathy SM, Thomson MJ, Togbé C, Dagaut P, Halter F, Mounaim-Rousselle C, 2009. An experimental and kinetic modeling study of n-butanol combustion. *Combust Flame*; 156:852–64.

Dernotte J, Mounaim-Rousselle C, Halter F, Seers P., 2010. Evaluation of butanol–gasoline blends in a port fuel-injection, spark-ignition engine. *Oil Gas Sci Technol*; 65:345–51.

Gu X, Huang Z, Cai J, Gong J, Wu X, Lee CF., 2012. Emission characteristics of a sparkignition engine fuelled with gasoline-n-butanol blends in combination with EGR. *Fuel*;93:611–7.

Feng R, Yang J, Zhang D, Deng B, Fu J, Liu J, et al., 2013. Experimental study on SI engine fuelled with butanol-gasoline blend and H2O addition. *Energy Convers Manage*; 74:192–200.

Emilio N, Teresa J, Roberto C, 2013. $CO_2$ emissions from a spark ignition engine operation on natural gas-hydrogen blends (HCNG). *Appl Energy*;101: 112e20.

Ritchie D, Guohong T, Hongming X, Shijin S, 2012. Ignition timing sensitivities of oxygenated biofuels compared to gasoline in a direct-injection SI engine. *Fuel*;99:72e82.

S. Iliev, 2014. Developing of a 1-D combustion model and study of engine characteristics using ethanol-gasoline blends. *Proceedings of the World Congress on Engineers*, Vol II, WCE 2014/ 978-988-19253-5-0.

S. Iliev, 2015. A comparison of ethanol and methanol blending with gasoline using a 1-D engine model. *Procedia Engineering*, Elsevier, Vol 100, pp. 1013-1022.

L. Raslavicius, Z. Bazaras, 2010. Variations in oxygenated blend composition to meet energy and combustion characteristics very similar to the diesel fuel, *Fuel Processing Technology* 91 (9) 1049–1054.

Egeback KE, Henke M, Rehnlund B, Wallin M, Westerholm R, 2005. Blending of ethanol in gasoline for spark ignition engines-problem inventory and evaporative measurements. *Report No. MTC 5407*. AVL MTC Motortestcenter AB Box 223 SE-136 23 Haninge.