The study of cyclic variability at a n-butanol spark ignition engine fueled

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Abstract. Alcohols such as ethanol, methanol and butanol have gained more attraction in recent years in the use of alternative fuels at the internal combustion engines (ICE) because of their good combustion properties. The use of the butanol-gasoline blends can lead to a decrease in greenhouse gases (CO\textsubscript{2}) and pollutants such as unburnt hydrocarbons (HC), carbon monoxide (CO) but may increase nitrogen oxides (NO\textsubscript{x}). An experimental study carried out on a spark ignition engine fueled with a n-butanol-gasoline blend (10\% vol. butanol - 90\% vol. gasoline) at an engine load $\chi=55\%$, speed of $n=2500$ rpm and different air excess ratios ($\lambda$). The objective of this paper is to determine the effects of n-butanol on combustion, specifically on the cyclic variability. So, the COV values for maximum pressure, indicated mean effective pressure and angles of mass fraction burned -10\%, 50\% and 90\%- are presented. The engine fueling with butanol-gasoline blend engine leads to the decrease of the cyclic variability and the COV values don’t exceed the recommended value. A great advantage of n-butanol use is the increase of the thermal efficiency due to the stable engine operation and at lean mixtures.

1. Introduction

Current worldwide fossil fuel consumption lead to a depletion of conventional fuels in a matter of decades, thus that more researches have been focused on alternative fuels. Great consumption of fossil fuel is also associated with greenhouse gases such as CO\textsubscript{2} and pollutants products, especially for passenger vehicles over the last years. For internal combustion engines, alcohols have gained a lot of attention in recent years. The use of the alcohols like methanol, ethanol or butanol - conventional fuels such as gasoline or diesel - blends can improve the combustion process in the engine cylinder and reduce fossil fuels consumption. Due to their better combustion proprieties, alcohols can increase the thermal efficiency for a given displacement and compression ratio, improve combustion resulting in lower fossil fuel consumption and thus lower CO\textsubscript{2} emissions [1-3]. A well-to-wheel analysis carried out by Wu. M. et al [4] concluded that on a life-cycle basis, the use of the corn based butanol as transportation fuel could reduce the consumption of gasoline by 39\%-56\% and reduce greenhouse emissions by up to 48\%.

When talking about spark ignition engines, the most widespread alcohol as use is ethanol, in Europe Euro 6 gasoline contains 10\% ethanol while in Brazil it is possible to completely fuel the vehicle with 100\% ethanol (flex fuel). In Nord America fuel blends can be sold up to 85\% ethanol and...
15% gasoline [5]. For car manufacturers it important to adapt their vehicles to run on both gasoline and gasoline-alcohol blends in order to achieve satisfactory durability and robust engine calibration. Standard vehicle fuelling systems are not designed to resist to alcohol’s corrosive properties such as ethanol. Butanol is a viable solution for blending with gasoline as its properties are much closer to those of gasoline and it’s also less corrosive properties than ethanol, thus reducing the efforts of Original Equipment Manufacturers (OEM) for the design of the cars [6]. Butanol also has a high tolerance to water contamination and it can blend with gasoline at high fractions without any vehicle modifications and may reduce fossil fuel consumption due to higher energy density [7].

There are many studies regarding the use of the alcohols-gasoline blends such as methanol, butanol or ethanol for fuelling spark ignition engines. For gasoline-butanol blends, a study conducted by Zswaja and Naber [8] investigated the effects of the spark timing, compression ratio, engine load and percentage of n-butanol on the combustion in a spark ignition engine cylinder. In a study by Alasfour [9] a single cylinder engine was fuelled with a 30% butanol-gasoline blend. The study concluded that there was a 7% decrease of the engine power comparative with gasoline because of smaller butanol lower heat value. Wallner et al. [10] studied the influences of 10% butanol in blend with gasoline on the emissions (HC, CO and NOx) in a modern direct injection four cylinders spark ignition engine. Results showed little differences of the HC, CO and NOx emissions level comparative with the gasoline at the engine operate at the stoichiometric dosage for 10% butanol-gasoline blend and pure gasoline. Rice et al. [11] studied the effects of the ethanol-gasoline blends, methanol-gasoline blends and iso-butanol-gasoline blends on pollutants. The study shows a decrease of the CO and NOx emissions level comparative with the gasoline. The effects of 30% butanol-gasoline blends on NOx emission level were studied by Alasfour [12]. In his study, he varied the intake air temperature (by preheating the air) and spark ignition timing. The NOx emissions level increased with 10% at the increase of the air temperature from 400 to 608°C. Furthermore increasing the intake air temperature causes knock and misfire at lesser advanced ignition timing so further ignition timing retarding is required. By doing this however, engine thermal efficiency will decrease [12]. Finally, also Alasfour [13] determined that at the increase of the spark ignition timing will increase NOx emissions level using a blend of 30% butanol-gasoline. D. Balaji [14] investigated the effects of iso-butanol-gasoline blends in a four stroke single engine cylinder. He measured engine performance parameters such as fuel consumption, brake thermal efficiency, brake power, torque and brake specific fuel consumption. The study shows that the addition of 5% iso-butanol and 10% ethanol yield the best results for all measured parameters at all engine torque values. J. Derron et al. [15] studied the effects of butanol-gasoline blends, at different percentages, on specific fuel consumption, pollutants and pressure variability in a spark ignition engine. It was observed that at a 40% butanol-gasoline blend the engine could run at leaner dosages that comparative with gasoline. Unburned hydrocarbons emissions level where similar to gasoline for 20% butanol-gasoline blend, (B20) and 40% butanol-gasoline blend, (B40) while using blends of over 60% butanol, (B60) will increase HC emissions level comparative with gasoline. The operation of the engine at stoichiometric and slightly lean dosages, NOx emissions level was similar for all blends, but for B80 (80% butanol-20% gasoline) NOx emission level decreased, HC emissions level increased due to combustion deterioration. The study shows a slight increase of the specific fuel consumption due to the butanol lower heat value. For butanol-gasoline blends, even in small percentages of butanol, the coefficient of variability of the indicated mean effective pressure (COV_{IMEP}) decreases because of the improvement of combustion [15]. The coefficient of variability of IMEP has been shown to impact vehicle drivability if it exceeds 10% as shown by Heywood JB [16]. The potential of n-butanol was studied by Zheng et al. [17] where combustion and emissions of a two stage injection engine were compared first at fueling with pure gasoline/diesel and then with diesel/n-butanol, and diesel/gasoline/n-butanol. Results show that blending gasoline and/or n-butanol in diesel improved the smoke emissions and the maximum pressure rise rate increased. Zheng [18] also studied the effects of butanol isomers (iso-butanol, sec-butanol, n-butanol and tert-butanol) on low temperature single-cylinder diesel engine. Compared to pure diesel, adding butanol isomers improved thermal efficiency, retarded combustion phasing and
also reduced soot emissions, a critical subject for diesel engines. In a study by J. Hunter et al. [19] studied the effects of n-butanol and iso-butanol at an automotive-scale HCCI engine in single-cylinder mode. Results shown that the indicated mean effective pressure was comparable for all fuels, but for n-butanol IMEP value accentuated increased. Both n-butanol and iso-butanol have improved combustion stability, however n-butanol was more stable under all conditions and misfire occurred later at the very lean mixtures use. The emissions level is similar to those of gasoline and ethanol but the NOx emissions level decreased due to HCCI operation. The study concluded that the butanol-gasoline blends use is a better choice compared to ethanol for their HCCI combustion properties.

Previous studies indicated an improvement of the combustion process by adding even of small percentages of butanol isomers in gasoline blend.

The objective of this paper is to study the effects of n-butanol-gasoline blend use on the combustion process at a car spark ignition engine.

2. Experimental test bench and procedures
The experimental test bench is presented in the figure 1:

![Test bench schema](image)

1 – ECU, 2 – dyno cooling system, 3 – dyno control cabinet, 4 – Eddy current dyno, 5 – throttle body actuator, 6 – A15MF engine, 7 – turbocharger, 8 – catalytic converter, 9 – radiator cooling system, 10 – gas analyzer, 11 – desktop, 12 – fuel mass flow transducer, 13 – air flow transducer, 14 – boost pressure transducer, 15 – fuel reservoir.

**Figure 1** Test bench schema

The engine used is with 4 cylinders, turbocharged, type 1,5l Cielo Nubira A15MF. The engine is fueled by gasoline and the experimental investigations carried out at the 55% engine load and speed of 2500 rpm; different parameters were recorded such as intake air and water temperature, fuel mass flow, air flow, boost pressure and emissions concentrations, engine power and speed. For the calculus of the cyclic variability, 250 consecutive combustion cycles are recorded with a resolution of 1 °CA
(crank angle). After setting the reference with gasoline, the same measurements are done at fueling of the engine with a blend of 90% gasoline and 10% n-butanol. In order to determine the cycle-to-cycle variation during combustion process, the coefficients of variability (COV) of maximum pressure, mean effective pressure (IMEP), the angles of 5%, 50% and 90% of mass fraction burnt (MFB), were calculated. The spark timing, the dosage and the engine power are kept at the same values.

3. Results

Below, in figure 2, the maximum pressure dispersion over 250 consecutive engine cycles is presented (drawn with blue –G when the engine is fueled only gasoline and drawn with red when the engine is fueled with GB10 - 90% gasoline and 10% butanol in blend). From the figure 2 we can see a bigger dispersion in values at fueling with gasoline. The coefficient of variability for maximum pressure is determined with the following formula [20]:

\[ \text{OV}_{\text{pMax}} = \frac{\sqrt{\sum_{k=1}^{N_c} (p_{\text{max},k} - p_{\text{max},m})^2}}{p_{\text{max},m}} \]  

where (1) represents the standard deviation and (2) the average value for maximum pressure.

![Figure 2](image)

**Figure 2** Maximum pressure dispersion at the engine fuelling with gasoline and gasoline-butanol blend

The variability coefficient for maximum pressure (COV)\(p_{\text{max}}\) at the fueling with gasoline is 13% while at the fueling with gasoline-butanol blend the (COV)\(p_{\text{max}}\) is 9.47%. This is presented in the figure 3, where \(x_c\) represents the substitute ratio of the gasoline with butanol. The reduction with ~ 4% of (COV)\(p_{\text{max}}\) at the fueling with butanol indicates an improvement of the combustion process stability due to the additional oxygen available for burning. The maximum pressure however is lower at the butanol fueling with 17% because the lower heat value of the butanol is lower comparative to gasoline and the combustion is displacement in expansion due to increase the initial combustion phase duration.

The indicated mean effective pressure (IMEP) dispersion is presented in the figure 4. Same as the maximum pressure, the dispersion is greater at engine fueling with gasoline; calculated (COV)\(\text{IMEP}_G\) is around 4.5% (for gasoline). The engine fueling with butanol in mixture with gasoline also indicates an improvement of the combustion process stability, see figure 4, where the dispersion is less noticeable. The use of butanol in mixture with gasoline brings a reduction of the (COV)\(\text{IMEP}\) with 38% comparative with gasoline.
Figure 3 (COV)p_max for different substitute ratios x_c

Figure 4 IMEP dispersion at the engine fueling with gasoline and gasoline-butanol blend

Figure 5 (COV)IMEP for different substitute ratios x_c

In the figure 6 is presented the crankshaft angle at which the maximum pressure is reached for gasoline and butanol - gasoline blend. We notice that for butanol -gasoline blend the maximum pressure is reached later comparative to gasoline; at gasoline the average angle for maximum pressure is 27°CA and for butanol -gasoline blend is 38°CA. The later ignition of the butanol- gasoline blend is influenced by the gases temperature, which is smaller because of the higher vaporization heat at
butanol and the initial combustion phase duration increases, [20]. The increase of initial combustion phase duration will cause that the maximum pressure to be reached later comparative to the gasoline.

In the figures 7 and 8 is presented a comparison between the pressure diagrams at fueling with gasoline and butanol-gasoline blend. The higher cyclic dispersion for gasoline comparative to gasoline-butanol blend is observed.

**Figure 6** Crank angle at which maximum pressure is achieved at fuelling with gasoline and gasoline-butanol blend over 250 cycles

**Figure 7** Pressure diagrams for gasoline
The angles of the mass fraction burned for 5\% heat released, $\alpha_{5\%}$ are represented in figure 9. The dispersion of the $\alpha_{5\%}$ is greater in both cases. The coefficient of variation for gasoline (COV)$_{\text{MFB} 5\%G}$ is 44, 83\% and the coefficient of variation for gasoline-butanol blend (COV)$_{\text{MFB} 5\%GB10}$ is 56, 54\%, and indicates a higher combustion stability of mass fraction burned 5\% for gasoline.

The higher oxygen content of the butanol improves the combustion process, influence which determines the earlier attainment of angle of the mass fraction burned for 50\% heat released, $\alpha_{50\%}$, 16\degree CA for gasoline-butanol blend vs 23 \degree CA for gasoline, figure 10. The dispersion value is smaller for gasoline-butanol blend comparative to gasoline, (COV)$_{\text{MFB} 50\%GB10} \approx 14\%$ respectively (COV)$_{\text{MFB} 50\%G} \approx 17\%$, figure 12.

The angles of the mass fraction burned for 90\% heat released, $\alpha_{90\%}$ are represented in the figure 11, (45 \degree CA for gasoline and 51 \degree CA for gasoline-butanol blend).

The dispersion values are reduced in both cases, the coefficient of variation being same, 0.5\%, for gasoline and gasoline-butanol blend.

The overall variation of (COV)$_{\text{MFB}}$ at $\alpha_{\%}$, $\alpha_{50\%}$ and $\alpha_{90\%}$ is presented in the figure 12.
4. Conclusions

The investigated engine operating regime results show that blending 10% volume of butanol with gasoline 90% volume improves the combustion process stability. The coefficient of variation for maximum pressure decreases from 13% for gasoline to 9.47% for gasoline-butanol blend. The coefficient of variation for the indicated mean effective pressure decreases from 4.5% for gasoline to 2.73% for gasoline-butanol blend. A smaller value of the \((\text{COV})_{\text{IMEP}}\) for gasoline-butanol blend
indicates a better combustion stability and ensures better drivability for vehicles. The good combustion properties of the butanol assure the decrease of the main combustion phase duration. The angle of the mass fraction burned for 50% heat released, $\alpha_{50\%}$, is reached earlier with 7°CA for the gasoline-butanol blend comparative to gasoline.

The experimental investigations results show that the butanol can be considered a good alternative fuel for automotive spark ignition engines.

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