

Butanol Blending – a Promising Approach to Enhance the Thermodynamic Potential of Gasoline – Part 1

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ABSTRACT

Blending gasoline with oxygenates like ethanol, MTBE or ETBE has a proven potential to increase the thermodynamic efficiency by enhancing knock resistance.

The present research focuses on assessing the capability of a 2- and tert-butanol mixture as a possible alternative to state of the art oxygenates. The butanol mixture was blended into a non-oxygenated reference gasoline with a research octane number (RON) of 97. The butanol blending ratios were 15% and 30% by mass. Both the thermodynamic potential and the impact on emissions were investigated.

Tests are performed on a highly boosted single cylinder gasoline engine with high load capability and a direct injecting fuel system using a solenoid actuated multi-hole injector. The engine is equipped with both intake and exhaust cam phasers. The engine has been chosen for the fuel investigation, as it represents the SI technology with a strongly increasing market share.

The blended gasoline-butanol mixtures showed a distinct increase in RON and MON numbers as well as in heat of vaporization. As a consequence, high and full load efficiency could be improved by earlier ignition timing and hence a more favorable centre of combustion could be attained. The indicated mean effective pressure (IMEP) could be increased by more than 20% in comparison to the reference gasoline at an equivalent level of coefficient of variance (COV) of IMEP. The gain in knock resistance could contribute to a significant reduction in CO₂-emissions when compression ratio is increased or when engine downsizing is realized. At low and medium loads, identical or slightly improved performance regarding thermodynamics and emissions could be detected.

With the ongoing discussion on the limitation of particulate emission from gasoline engines, the observed capability of butanol blends to reduce soot particle mass and number especially at cold engine conditions can be regarded as a positive impact of the butanol blends when compared to the non-oxygenated gasoline.

This study underlines the high potential of the investigated 2- and tert-butanol mixtures to serve as oxygenates for blending into gasoline in order to achieve higher fuel quality levels. Furthermore, detailed investigations including multi cylinder engine experiments are planned for part 2.

INTRODUCTION

CO₂-emission reduction by enhanced thermodynamic efficiency and reduced soot and particle emissions are the main challenges in the current development of gasoline engines and fuels. One fuel component with a high public visibility for use as a blend agent in gasoline is ethanol. Ethanol blends have shown to improve full load behavior due to the high knock resistance and heat of vaporization, and thereby to offer potential for higher compression ratios or downsizing levels [1, 2]. However at higher blending rates ethanol reveals drawbacks especially when it comes to material compatibility considerations and phase-separation issues in the presence of water.

Within recent years a clear trend towards higher levels of oxygenates can be noticed. For instance current EU legislation has extended the upper limit on the oxygen content of gasoline to 3.7% (m/m). Despite the well known benefits of alcohols and ethers like ethanol or ETBE, it is of clear interest to investigate other possible options that might offer significant potential like the four carbon alcohol butanol.

Previous publications state that gasoline blends with butanol reveal a potential in enhancing thermal efficiency and are less susceptible to phase separation as a result of water ingress than blends containing ethanol. Moreover, regarding the same oxygen content, butanol blends allow a greater volume of crude-oil derived gasoline displacement than ethanol [3], [4]. Detailed investigation on the performance of a 4 cylinder DI-SI engine have shown that n-butanol gasoline blends of 10% slightly deteriorate the engine full load performance when compared to pure gasoline, but improve volumetric fuel consumption compared to E10, at a RON level of approximately 90 [5]. Recent investigation of pure n-butanol [6] showed that n-butanol produced slightly less brake torque than gasoline. Hydrocarbons emissions were significantly increased above those of gasoline suggesting that DI mixture formation of n-butanol is deteriorated compared to gasoline. The mixture formation and combustion of gasoline, ethanol and butanol have been detailedly investigated including optical measurements of the spray development and combustion in a DI single-cylinder engine for part load operation by [7]. Different levels of butanol blending have been investigated in a PFI multicylinder engine [8], leading to the result that blending of 40% of butanol minimizes HC emissions, improves combustion stability and enleanment capability in terms of combustion stability with a comparable fuel consumption to gasoline.

The present research focuses on investigating the thermodynamic capability of a 2- and tert-butanol mixture to serve as a future blend agent for gasoline at a high RON level of 97 and above. The study comprises of DI TC single cylinder engine testing at full load and part load operation with different compression ratios.

FUEL PROPERTIES

Two butanol blends were produced by adding a mixture of 2- and tert-butanol at rates of 15% (B15) and 30% (B30) by mass, to a non-oxygenated premium gasoline that also acted as a reference base fuel. As shown in *table 1* the base fuel reveals an already comparatively high RON number of 97. Using the 2- and tert-butanol mixture as a splash blend agent, both RON and MON can be increased. However, higher blend rates do not increase the RON linearly.

Furthermore butanol blending has the following effects on fuel properties:

- lower heating values
- higher density
- a decrease in DVPE, which can be favorable in climate regions with higher temperatures and also for summer fuel qualities in moderate climate
- an increase in heat of vaporization which is favorable when applying direct injection, due to a higher in-cylinder charge cooling effect
- linearly increasing oxygen content, with 3% (by mass) for B15 and 6% (by mass) for B30

	Unit	Base fuel	B15	B30
RON	-	97.0	99.5	100.2
MON	-	88.2	89.2	91.6
Heating value	MJ/kg	43.2	42.1	41.0
Density @ 15 °C	kg/m ³	740.7	748.0	755.9
DVPE	kPa	61.1	58.2	54.5
Heat of vaporization	kJ/kg	approx. 420	approx. 456	approx. 491
Sulphur content	mg/kg	23.0	17.0	13.2
Distillation yield	%(v/v)	97.5	98.6	98.4
C-Content	%(m/m)	86.4	83.5	80.3
H-Content	%(m/m)	13.5	13.5	13.6
O-Content	%(m/m)	0.0	3.0	6.1
Aromatics	%(v/v)	34.7	30.4	24.8
Olefins	%(v/v)	2.5	2.1	1.9
Saturated HC	%(v/v)	62.6	53.5	45.2
Alcohol content	%(m/m)	0.0	14.9	29.8

Table 1: Overview of fuel properties, RON / MON determined according to DIN5164 / 5163

The vaporization curves of the fuels reveal that higher blending rates accelerate vaporization when exceeding a temperature of approximately 75 °C.

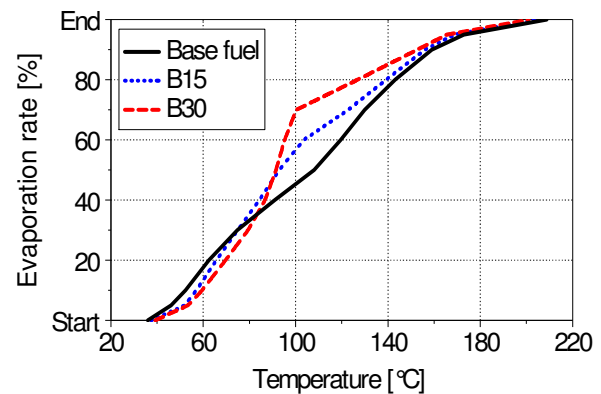


Figure 1: Evaporation curves

Due to the reduced content of volatile components of the butanol blended fuels can be expected to have some drawback in mixture formation at lower temperature, e.g. during engine cold start and warm up operation.

TEST BENCH SETUP

Tests were conducted on a single cylinder research engine designed for high load applications. The features of the engine comprised:

- Displacement: 364.0 ccm
- Bore: 75 mm
- Stroke: 82.5 mm
- Mechanical valve train with two overhead camshafts and four valves
- Intake and exhaust cam phasers with 40 °CA range, event length intake and exhaust 186 °CA
- Solenoid actuated multi-hole injector with up to 150 bar rail pressure
- External air charging and exhaust back pressure valve to simulate a turbocharged engine

- Capability of applying cooled external EGR

Engine tests were performed at different compression ratios realized by different piston designs. A flexible programmable engine control unit was utilized to run the engine. The intake and the exhaust port were equipped with low pressure sensors. Within the cylinder two redundant pressure transducers were used and combustion was analyzed using the FEV system CAS. In order to run the engine at certain water, oil and intake air temperatures, conditioning devices were implemented. Fuel consumption was determined by using a mass fuel flow sensor. Moreover a lambda sensor was integrated into the exhaust pipe as well as an emission sampling system, analyzing the concentrations of oxygen, nitrogen oxides, hydrocarbons, carbon monoxide and carbon dioxide. Soot number, particle mass concentration and particle number were measured using an AVL smoke meter and a TSI CPC, respectively.

The test matrix includes investigations to assess the performance of the butanol blends at several steady state operation points consisting of low, medium, high and full load as well as different engine speeds. The investigated points address the NEDC (New European Driving Cycle) as well as customer relevant operation. Two compression ratios have been investigated. A representative compression ratio for advanced series production TC-DI SI engine is CR 10. Additionally CR 12 is investigated due to its higher fuel consumption potential in NEDC cycle relevant operation. For both compression ratios CR 10 and CR 12 the following operating points have been investigated:

High to Full Load Operation

- Load sweep from 10 bar IMEP knock limit at 1500, 2500 and 4000 rpm (coolant and oil 90 °C)

Part Load Operation:

- Start of injection (SOI) variation at 1000 rpm and 6 bar IMEP (coolant and oil 90 °C)
- Start of injection (SOI) variation at 2000 rpm and 3 bar IMEP (coolant and oil 50 - 90 °C)

Catalyst heating operation:

- Start of injection (SOI) variation at 2000 rpm and 3 bar IMEP (coolant and oil 50 - 90 °C)

The results presented in the following chapters focus on operating conditions, under which noticeable and systematic differences between the fuels have been obtained.

EXPERIMENTAL RESULTS

HIGH AND FULL LOAD

In order to assess the high load capability of the butanol blends, load sweeps at 1500, 2500 and 4000 rpm were performed. The results for the compression ratio of 12.0 are illustrated in *figures 2-4*.

The load sweeps start at 10 bar IMEP. For each sweep constant injection timing and valve timing was applied. The incremental increase is 2 bar IMEP until the knock limit is reached. The knock limit is defined here as the point where the combustion stability

reaches a defined limit of COV of IMEP in combination with the required ignition retard to achieve an acceptable knocking intensity.

Due to intensified knocking with increased engine load, ignition timing has to be retarded. The limit for minimum ignition retardation is defined here by a knock peak-to-peak value of 2.25, 3.75 and 6 bar for 1500, 2500 and 4000 rpm.

As a consequence of the ignition retard both the peak pressure positions and the MFB 50% are shifted to later timings and the COV of IMEP increases. As a general effect knock limitation decreases with higher engine speed for all three fuels. In order to quantify the maximum achievable IMEP a limit of retardation of the MFB 50% of 27.5 °CA ATDC is applied here at 2500 and 4000 rpm, and 32.5 °CA ATDC at 1500 rpm. These limits have been chosen, because they correspond to a reasonable low level of COV of IMEP (approx. 2% at 1500 rpm and 3% at 2500 and 4000 rpm).

The effect of the knock limitation required ignition time retardation can be clearly seen in *figure 2*. At the medium load of 10 bar IMEP all fuels are knock limited, and the ignition timing retard is identical. Interestingly, at this medium load the differences in combustion behavior between the base, B15 and B30 are comparatively small. The burn delay (ignition timing – MFB 10%) is identical for all fuels, and the burn duration (MFB 10% - MFB 90%) is only marginal longer for the base fuel. This result shows that the combustion performance of the fuels in warm engine conditions and comparable knock limitations is rather similar, which can also be seen from the identical fuel consumption ISFC and combustion stability COV at 10 bar IMEP.

With increased load of 14 bar IMEP, *figure 2* shows that the reduced knock sensitivity of B30 enables an earlier ignition, which in turn leads to a reduced burn duration and improved COV, compared to the base fuel and B15. With further increased load the curves for base fuel, B15 and B30 diverge almost constantly, until the base fuel reaches the maximum IMEP of 16.2 bar due to the combined knock and stability limit. Both B15 and B30 do not reveal such a steep increase of COV when approaching the maximum IMEP.

At engine speeds of 2500 and 4000 rpm, *figures 3 and 4*, comparable effects of fuel performance are observed, which are mainly influenced by the improved knock resistance of B15 and B30. No significant differences in combustion characteristics such as burn duration between MFB 10%, 50% and 90% are observed between base fuel and butanol blends, if one considers an identical position of ignition retardation.

In conclusion, B30 shows the highest knock resistance for all three engine speeds. As a result ignition timing can be advanced achieving higher efficiency. Comparing the achieved load at a constant MFB 50% position of 27.5 °CA ATDC an increase of IMEP by approximately 2.5 bar at 1500 rpm and 4.0 bar at 2500 and 4000 rpm can be obtained by