Combustion and Emissions of a Small SI Engine with Butanol Blend Fuels

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Abstract. The bioalcohols are an important alternative in the general efforts to replace the fossil fuels in transportation by renewable fuels. The global share of Bioethanol used for transportation is continuously increasing. Butanol, a four-carbon alcohol, is considered in the last years as an interesting alternative fuel, both for Diesel and for Gasoline application. Its advantages for engine operation are: good miscibility with gasoline and diesel fuels, higher calorific value than Ethanol, lower hygroscopicity, lower corrosivity and possibility of replacing aviation fuels. In the present work research with different Butanol portions in gasoline (BuXX) was performed on the 2-cylinder SI engine with variations of several parameters on engine dynamometer. In the steady state operation, it was found that Bu-blends generally reduce the emissions of CO, HC, NOx in untreated exhaust gas and have a very little influence on catalytic conversion rates of the 3-way-catalyst. At lower engine part load, “Bu” shortens the inflammation lag and reduces the cyclic dispersion of combustion. Nevertheless, this advantage disappears at higher engine loads and with higher “Bu” portions. The present paper shows some examples of the most important results.

1. Introduction
Butanol (CH3(CH2)3OH) has a four-carbon structure and is a higher-chain alcohol than Ethanol, as the carbon atoms can either form a straight chain (n-Butanol) or a branched structure (iso-Butanol), thus resulting in different properties. Consequently, it exists as different isomers depending on the location of the hydroxyl group (-OH) and carbon chain structure, with Butanol production from biomass tending to yield mainly straight chain molecules. 1-Butanol, better known as n-Butanol (normal Butanol), has a straight-chain structure with the hydroxyl group (-OH) at the terminal carbon.

n-Butanol is of particular interest as a renewable biofuel as it is less hydrophilic, and possesses higher energy content, higher cetane number, higher viscosity, lower vapour pressure, higher flash point and higher miscibility than Ethanol, making it more preferable than Ethanol for blending with diesel fuel. It is also easily miscible with gasoline and it has no corrosive, or destructing activity on plastics, or metals, like Ethanol or Methanol.

Several research works were performed with different Butanol blends BuXX, [1-9]. Generally, there are advantages of higher heat value (than Ethanol). The oxygen content of Butanol has similar advantages, like with other alcohols: tendency of less CO & HC, but possibility of increasing NOx (depending on engine parameters setting).

The good miscibility, lower hygroscopicity and lower corrosivity make Butanol to an interesting alternative.
The trend of downsizing the SI-engines in the last years implies much higher specific torques and with it an aptitude of knocking and mega-knocking at high- and full load. The alcohols have a higher Octane Numbers (RON), are more resistant to knocking and are a welcomed solution for this new technology of engines, [1].

A basic research of butanol blends Bu20 & Bu100 was performed on mono-cylinder engines with optical access to the combustion chamber, [2, 3]. One of the engines was with GDI configuration. It was demonstrated, that the alcohol blend improved the internal mixture preparation and reduced the carbonaceous compounds formation and soot.

Concerning the characteristics of combustion Bu100 was similar to gasoline. This research considered only little number of constant operating points.

Using n-Butanol in a optical port fuel injection (PFI) SI engine slightly higher combustion rates and lower formation of particulates was found compared to gasoline, [4, 5]. Similarly [6] reported that the duration of the early combustion stage and length of combustion in an SI engine were, compared to gasoline, shortened with increased n-butanol share, and slightly lower variability of indicated mean pressure (IMEP) was observed when running on neat n-butanol. Shorter early combustion stage, faster combustion and better combustion stability were also observed by other researchers [7, 8].

The alcohol blend fuels E85 & Bu85 were tested on a vehicle with 3WC in road application and with on-board measuring system for exhaust emissions, [9]. It was stated for butanol, that it has no significant influence on CO & HC, but it increases strongly NO\textsubscript{x}. Nevertheless, this is due to the limits of Lambda regulation and as effect of it to the production of too many lean Lambda excursions during the transients.

The warm operation with Bu85 was with no problems, the cold startability and emissions were not investigated.

The presented tests were performed in the IC-Engines Laboratory of the University of Applied Sciences, Biel, CH within the framework of project GasBut (Gasoline + Butanol). The research objectives were:

- full load (FL) characteristics,
- variations of spark timing (\(\alpha_z\)),
- research of lean operation limit at part load (\(\lambda\)-variations),
- research of EGR limit at part load (EGR-variations),
- research of knock limit at FL.

With this research, it was possible to investigate the influences of fuel quality on engine internal processes as well as on the standard exhaust aftertreatment (3WC).

The research was performed with Bu0, Bu30, Bu60 and Bu100.

2. Test Engine, Fuels and Lubricants

2.1. Test engine

Figure 1 shows the engine on the engine dynamometer and Table 1 summarizes the most important engine data.

The research was conducted on a Lombardini 2-cylinder SI-engine 0.5L. This engine is equipped with a programmable control unit, which allows a flexible parametrization of spark timing and equivalence ratio. There is a combustion chamber pressure indication with data acquisition and processing, which allows an accurate combustion diagnostic. The test bench with eddy-current dynamometer is equipped with analysis of limited exhaust gas components.
Table 1. Engine specification Lombardini LGW523.

| Engine specification | Lombardini LGW523 |
|----------------------|---------------------|
| Manufacturer         | Lombardini          |
| Type                 | LGW 523             |
| Cylinder             | 2 in-line           |
| Displacement [dm³]   | 0.505               |
| Compression ratio    | 8.7 : 1             |
| Rated speed [rpm]    | 5000                |
| Rated power [kW]@ 5000 rpm | 15               |
| Combustion process   | multipoint fuel injection |
| Catalyst             | no at this stage    |

Figure 1. Test engine on the engine dynamometer.

2.2. Fuels

Following base fuels were used for the research:
- gasoline (RON 95) from the Swiss market
- n-Butanol or i-Butanol from Thommen-Furler AG.

As blend fuels were used: Bu30, Bu60 and Bu100 (30% vol, 60% vol Butanol and respectively neat Butanol 100% vol).

Table 2 represents the most important data of the fuels (according to the literature sources).

Table 2. Fuel properties of the test fuels

| Specification         | RON 95 | n-Butanol | Bu30 | Bu60 | i-Butanol |
|-----------------------|--------|-----------|------|------|-----------|
| Other name            | Gasoline, Bu0 | 1-Butanol |      |      | 2-Butanol |
| Formula               | -      | C₄H₁₀O    |      |      | C₄H₁₀O   |
| Density [kg/dm³]      | 0.737  | 0.806     | 0.759| 0.781| 0.803     |
| Stoichiometric AF-ratio [kg air] | 14.70  | 11.10     | 13.55| 12.46| 11.10     |
| Lower heating value [MJ/kg] | 42.70  | 33.12     | 39.60| 36.60| 32.92     |
| O₂ fraction [% m]     | 1.70   | 21.62     | 8.08 | 14.10| 21.62     |
Boiling range [°C] 38-175 118 99
Blending RON 95 99 105
Blending MON 87 84 91
Self-ignition temperature [°C] 300 343
Flash point [°C] <-40 34 30
Viscosity @ 40°C [mPa*s] 0.83 2.90 3.00

It can be remarked that with increasing share of Butanol the Oxygen content of blend fuel increases and the heat value and stoichiometric air requirement decrease.

2.3. Lubricant
For all tests, a special lube oil MOTUL 300V Le Mans 20W-60 was used.

3. Test methods and instrumentation

3.1. Engine dynamometer and standard test equipment
Fig. 2 represents the special systems installed on the engine, or in its periphery for analysis of emissions and for combustion diagnostics.

In the present work, an EGR-system (EGR-line, valve and cooler) was installed on the engine. The EGR-rate is estimated by means of CO₂-measurement in exhaust and intake of the engine.

![Figure 2. Measuring set-up on engine dynamometer.](image-url)
Table 3 shows the used laboratory equipment of the engine dynamometer. Different parameters are registered on-line via PC. The continuous registration of all parameters is possible.

Table 3. Laboratory equipment used for tests.

| Equipment                  | Type                      |
|----------------------------|---------------------------|
| Eddy current brake         | Schenk W40                |
| Air-flow sensor            | Bosch HFM 5               |
| Lambda sensor              | ETAS LA3                  |
| Data acquisition           | Dspace 1103               |
| Temperature measurement    | Thermo-couples Type K     |
| Pressure measurement       | Saurer pressure measurement 82 |

3.2. Test equipment for regulated exhaust gas emissions
The gaseous components CO₂, CO, HC₉R, NOₓ, O₂ were measured with analyzers Horiba VIA-510 and HC₉FID was measured with Testa FID 123 with heated line.

3.3. Combustion diagnostics – pressure indication
During all tests, cylinder pressure was indicated, so that the combustion characteristics could be valued in each case. Therefore, following devices were used, see Table 4.

Figure 3 gives an example of indicated pressure and of heat release, which are analyzed at all operating conditions of the engine.
Table 4. Equipment used for the combustion diagnostics.

| Equipment          | Type                      |
|--------------------|---------------------------|
| Spark Plug / Pressure Sensor | Kistler 6117BFD16         |
| Charge Amplifier   | Kistler 5011B             |
| Signal Conditioner | Kistler 5219A             |
| Crank Angle Adapter| Kistler 2612C             |
| Combustion Analysis| Datac compact             |

4. Test procedures on engine dynamometer

The stationary testing was performed at different constant operating points (OP’s) of the engine. These OP’s were chosen at different speeds and at different loads. One part shows the full load characteristics and the other part represents partial load. The operating points in the engine map for entire test program show Fig. 4 and Table 5.

![Engine map of the Lombardini LGW523 engine and tested OP’s.](image)

Figure 4. Engine map of the Lombardini LGW523 engine and tested OP’s.

Table 5. Description of OP’s.

| OP  | n [rpm] | M [Nm] | p_m [bar] |
|-----|---------|--------|-----------|
| 1   | 2000    | 8      | 2.0       |
| 2   | 2800    | 6      | 1.4       |
| 3   | 2000    | 15     | 3.7       |
| 4   | 2800    | 11     | 2.7       |
| 5   | 2800    | 18     | 4.5       |
| 6   | 3500    | 14     | 3.6       |
| 12  | 4200    | 6      | 1.4       |
| 13  | 2100    | 10     | 2.6       |
| 14  | 2100    | 22     | 5.0       |
| 7   | 2000    | 38     | 9.3       |
| 8   | 2800    | 32     | 7.1       |
| 9   | 3500    | 35     | 8.6       |
| 10  | 4200    | 32     | 7.1       |
| 11  | 5100    | 28     | 6.0       |
5. Results

5.1. Variations of spark timing $\alpha_z$

Variation of spark advance at engine part load can be performed in two ways: at constant OP (n/M), or at constant throttle position. Both variants of tests have been performed with all investigated fuels at different OP's.

Fig. 5 shows the gaseous emissions at higher part load and Fig. 6 represents some combustion characteristics at lower and at higher part load. These pictures represent mostly the advantages of Butanol blends. Nevertheless, the complete picture, which results from all tests (4 OP’s not represented here) shows some limited or some neutral results.

Following tendencies can generally be remarked with increasing share of nButanol in the blend fuel:
- no effect on CO at low load, increased CO at higher load,
- lowering of HCFID,
- no effect on NOx at low load, clear reduction of NOx at higher load especially with nBu100,
- lowering of CO$_2$,
- $\alpha_z$ for $\alpha_{50\%}@9^\circ\text{CA b. TDC}$ generally later for BuXX,
• lower cyclic irregularities, quicker combustion and higher $p_{\text{max}}$ at low load, inversely at high load.

For comparisons: nBu100 $\rightarrow$ iBu100 it can be remarked that iBu100 causes:
• higher HCFID at low load and no clear differences (against nBu100) at higher load,
• generally lower CO- and higher CO$_2$ values,
• generally lower NO$_x$ values,
• no differences of inflammation phase, combustion duration, COV and $p_{\text{max}}$.

Generally, the findings at part load could be confirmed: with increased share of Butanol there is lowering of NO$_x$, HC and CO. The necessary spark timing ($\alpha_{\text{opt}}$) is nearer to the TDC, the maximum pressure rise is higher and the cyclic irregularities of combustion are lower. All these are signs of accelerated and improved inflammation phase. These effects of improved combustion are more pronounced at OP1 (lowest engine speed & torque) than at higher OP4 and OP6.

5.2. Variations of Lambda $\lambda$
These variations were also performed with all fuels at different engine operating points. Figures 7 & 8 represent an example from the lowest part load OP.

![Figure 7. Emissions during Lambda variation @ low partial load.](image1)
![Figure 8. Combustion & specific energy consumption during Lambda variation @ low partial load.](image2)

Increasing of Lambda was performed up to the lean operation limit, which was attained at strong increasing of cyclic irregularities (high values of COV) and increasing of HC.

The lean limit for this engine was:
- at OP2: $\lambda = 1.10 – 1.15$
- at OP4: $\lambda = 1.15 – 1.20$
- at OP5: $\lambda = 1.25$
The reason for this tendency is the lowering of the internal residual gas content with the increasing engine load. The diagrams of results in function of $\lambda$ show the comparisons between the fuels. With increasing of Butanol content following tendencies can be remarked:

- lower HC-values and lower HC-increase at lean limit,
- lower maximum values of NO$_x$,
- shorter inflammation phase ($IP = \alpha_{5\%} - \alpha_{z}$), especially with Bu60 & Bu100,
- lower cyclic dispersion (COV) at lean limit.

Comparisons of fuels at $\lambda \approx 1.10$ and $\alpha_{zopt}$ confirm these statements. With increasing BuXX there are:

- reduction of HC
- shortening of IP (except OP2) and reduction of COV.

There are also tendencies of reducing NO$_x$ and lowering $T_{exh}$ with the higher Butanol content. Summarizing: the present results of Lambda variations confirm the statements from previous tests. Butanol blended to gasoline slightly shortens the inflammation phase and lowers the cyclic irregularities of combustion at part load operation of the engine. It moves the lean operation limit to higher $\lambda$-values and it has positive influences on lowering NO$_x$ and HC.

5.3. Variations of EGR

The variations of EGR at part load were initially performed at OP4 with all fuels (Bu 0/30/60/100).

General tendency was found, that the higher Bu-content enables higher EGR-rate at the same COV (cyclic dispersion). This is a result of improved inflammation with Butanol.

At OP12 there was only a limited possibility of realizing EGR (gasoline up to 1%, Bu 100 up to 6%), but the effects of increasing Bu-content were well visible.

![Figure 9. Emissions during EGR Variation @ partial load.](image)

![Figure 10. Combustion & specific energy consumption during EGR variation @ partial load.](image)

Figures 9 & 10 give examples of emissions and combustion parameters at OP5.
The findings are confirmed: with increasing Butanol share at part load there is an improved inflammation, the IP-duration is shortened, and higher EGR-rates can be attained (at COV = idem). The combustion duration is only slightly shortened with higher Bu60 and Bu100. The gaseous emission components CO, HC, NOx are generally reduced with higher BuXX.

Summarizing: there are positive effects of Butanol on inflammation at part load, which enable application of higher EGR-rates. There are also positive influences of Butanol on emissions and on the specific energy consumption.

5.4. Knocking
The objective of this part of tests was to confirm the potentials of iButanol (with higher RON) concerning knocking. It was necessary to approach slightly the knock limit and indicate the knocking with a very low intensity to avoid damaging the engine. The chosen OP was WOT at 2100 rpm with variation of spark timing and the compared fuels were: gasoline and iBu100.

Fig. 11 represents cyclic dispersion of indicated pressure traces and samples of cycles without and with weak knocking.

To recognize weak knocking (weak oscillations, or irregularities on the indicated pressure signal) methods with differentiation of pressure (dp/da) or with ROHR (dQ/da) are applied. The second one, according to [2], was applied in the present tests.

Fig. 12 confirms the advantages of iBu concerning knocking: advancing spark timing (αz) the very weak knocking starts to be recognized with iBu at αz, which is more than 10°CA b.TDC earlier than with gasoline. Until the end of αz-variation range (70°CA b.TDC) the knocking with iBu stays very weak (Ki = 0.4%), while with gasoline the knock probability increases (up to Ki = 3.6%). In other words: the use of iBu moves the knock limit at FL to the higher values of spark advance. This can offer clear advantages of power and of fuel consumption in modern engines with higher compression ratio and with electronic knock control system.

**Figure 11.** Examples of knocking cycles.
6. Conclusions
The most important statements can be summarized as follows:

- The operation with Butanol blended to gasoline is possible without any problem. With neat Butanol (Bu100) nevertheless the cold start is problematic (with engine motoring).
- The lower overall heat value of BuXX-blends leads to a respectively lower full load torque without corrections of fuel dosing.
- The $\alpha_z$-variations at part load of the engine show lowering of HC, NOx & $\sigma_{pmi}$ with increasing Butanol rate.
- The improvements of combustion at part load are not observed at full load and with higher Bu-content there is even longer inflammation phase and longer combustion duration.
- IsoButanol causes lower CO-, higher CO$_2$- and lower NOx values than nButanol, the development of combustion is affected by isoButanol, in the same way as by nButanol.
- The $\lambda$-variations at part load of the engine show lowering of HC, NOx & COV with increasing Butanol rate.
- Butanol blended to gasoline slightly shortens the inflammation phase and lowers the cyclic irregularities of combustion at part load operation of the engine.
- With higher Bu-content the lean operation limit at part load is moved to higher $\lambda$-values.
- Higher Bu-content enables higher EGR-rate at the same COV (cyclic dispersion).
- There are positive influences of Butanol on emissions and on the specific energy consumption.
- Concerning knocking: the use of iBu moves the knock limit at FL to the higher values of spark advance.

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References
[1] Brassat A, Thewes M, Mütter M and Pischinger S 2011 Massgeschneiderte Kraftstoffe aus Biomasse für Ottomotoren MTZ 12/2011 988
[2] Marchitto L, Mazzei A, Merola S S, Tornatore C and Valentino G 2013 Optical investigations of combustion process in SI and CI engines fuelled with butanol blends TAE Technische Akademie Esslingen 9th International Colloquium Fuels
[3] Irimescu A, Tornatore C, Merola S S and Valentino G 2015 Integrated diagnostics for combustion investigation in a DISI engine fueled with butanol and gasoline at different load settings TAE 10th International Colloquium Fuels Stuttgart/Ostfildern 01/15 117
[4] Tornatore C, Marchitto L, Valentino G, Corcione F E and et al 2012 Optical diagnostics of the combustion process in a PFI SI boosted engine fueled with butanol-gasoline blend Energy 45 Issue 1 277-287 doi: 10.1016/j.energy.2012.03.006
[5] Merola S, Tornatore C, Marchitto L, Valentino G and et al 2012 Experimental investigations of...
butanol-gasoline blends effects on the combustion process in a SI engine *International Journal of Energy and Environmental Engineering* ISSN 2251-6832 doi: 10.1186/2251-6832-3-6

[6] Szwaja S and Naber J D 2010 Combustion of n-butanol in a spark-ignition IC engine *Fuel* 89 Issue 7 1573-1582 doi:10.1016/j.fuel.2009.08.043

[7] Gu X, Huang Z, Cai J, Gong J and Lee Ch 2012 Emission characteristics of a spark-ignition engine fuelled with gasoline-n-butanol blends in combination with EGR *Fuel* 93 611-617 doi:10.1016/j.fuel.2011.11.040
[8] Dernotte J, Mounaim-Rousselle C, Halter F and Seers P 2010 Evaluation of butanol-gasoline blends in a port fuel-injection, spark-ignition engine *Oil Gas Sci Technol - Rev IFP* **65** 345-51 doi: 10.2516/ogst/2009034

[9] Vojtisek-Lom M, Pechout M and Mazac M 2013 Real-word on-road exhaust emissions from an ordinary gasoline car operated on E85 and on butanol-gasoline blend *SAE Technical Paper* 2013-24-0102

**Abbreviations**

| Abbreviation | Description |
|--------------|-------------|
| A/F          | air/fuel ratio |
| AFHB         | Abgasprüfstelle FH Biel, CH |
| BAFU         | Bundesamt für Umwelt |
| BfE          | Bundesamt für Energie |
| BMEP         | break mean effective pressure |
| B/S          | bore/stroke |
| Bu           | Butanol |
| Bu85         | Butanol 85% vol |
| BuXX         | Butanol content XX% |
| CA           | crank angle |
| CO           | carbon monoxide |
| CO₂          | carbon dioxide |
| COV          | coefficient of variance |
| dQ/da        | ROHR, rate of heat release |
| EGR          | exhaust gas recirculation |
| EV           | Erdölvereinigung |
| E85          | Ethanol 85% v |
| FL           | full load |
| FID          | flame ionisation detector |
| GasBut       | Gasoline Butanol project |
| GDI          | gasoline direct injection |
| HC           | unburned hydrocarbons |
| Hₜ₀         | lower heat value |
| IMAP         | intake manifold pressure |
| IP           | inflammation phase αₖ until 5% heat release |
| Kᵢ           | [%] of knocking cycles, knock intensity |
| Kₓ           | conversion (reduction) efficiency of the component “X” |
| Lₑ₀         | stoichiometric air requirement |
| LGW          | Lombardini Gasoline Watercooling |
| LHV          | lower heat value |
| m            | mass |
| M            | torque |
| MFB          | mass fraction burned, heat release |
| MON          | Motor Octane Number |
| MPI          | multi point port injection |
| n            | engine speed |
| N₂           | nitrogen |
| NO           | nitrogen monoxide |
| NO₂          | nitrogen dioxide |
| NOₓ          | nitric oxides |
| OP           | operating point |
| pₘₐₓ         | maximum cylinder pressure |
| pₑₘₑ         | b.m.e.p (brake mean effective pressure) |
| pₑₘᵢ         | mean indicated pressure |
| RON          | Research Octane Number |
| sdevpₑₘᵢ     | standard deviation of mean indicated pressure |
| SI           | Spark Ignition |
| tₑₓₕₑ       | temperature measured near λ-sensor |
| TDC          | top dead center |
| TWC          | three way catalyst |
| WOT          | wide open throttle |
| α₅₀%         | crank angle of 50 % heat release |
| αₖₚₑ        | α first knocking peak (on the pₐᵦ signal) |
| αₚₑₘₓ       | crank angle of pₘₓ |
| αₚₑ         | spark angle |
| Δₚₑₘₓ       | max. rate of pressure raise |
| σₑₘᵢ        | standard deviation of mean indicated pressure |
| σₑₒₜₑ       | optimum spark timing [deg. CA b. TDC] for the best torque |
| λ            | air excess factor (mair / mair stoichiometric) |
| 3WC          | three way catalyst |