2018-32-0058/20189058 Published 30 Oct 2018

Influences of Butanol Blends on Combustion and Emissions of a Small SI Engine

Jan Czerwinski, Martin Güdel, and Danilo Engelmann University of Applied Sciences Biel-Bienne

Martin Pechout Technical University of Liberec

Citation: Czerwinski, J., Güdel, M., Engelmann, D., and Pechout, M. "Influences of Butanol Blends on Combustion and Emissions of a Small SI Engine," SAE Technical Paper 2018-32-0058, 2018, doi:10.4271/2018-32-0058.

Abstract

In the general efforts to replace the fossil fuels in transportation by renewable fuels the bioalcohols are an important alternative. 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 nButanol portions in gasoline (BuXX)* was performed on the 2-cylinder SI engine with variations of several parameters on engine dynamometer. At different steady state operating points were varied: spark timing (α_z), air excess factor (λ) and EGR-rate. Furthermore, the conversion rates and light-off of a 3-way-catalyst were investigated. As research tools the combustion pressure indication and the exhaust gas analysis were used.

In the steady state operation, it was found that Bu-blends generally reduce the emissions of CO, HC, NO_x 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.

* Abbreviations see at the end of this paper

Introduction

Butanol ($CH_3(CH_2)_3OH$) 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, 2, 3, 4, 5, 6, 7, 8, 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 NO_x (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 monocylinder 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_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.

In [10], nButanol was injected in the intake port of a DI-Diesel engine operated with biodiesel. This partial premixed charge compression ignition (PCCI) created a great reduction of soot- and NOx-emissions at part load operation of the engine.

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 (αz).
- research of lean operation limit at part load (λ-variations).
- research of EGR limit at part load (EGR-variations).
- influences on light-off and on catalytic conversion rates of 3-way-catalyst (3WC).
- 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.

Test Engine, Fuels and Lubricants

Test Engine

Fig. 1 shows the engine on the engine dynamometer and Tab. 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 parametrisation of spark timing and equivalence ratio. There is a combustion chamber pressure indication with data acquisition and processing, which allows an accurate combustion diagnostics. The test bench with eddy-current dynamometer is equipped with analysis of limited exhaust gas components.

FIGURE 1 Test engine on the engine dynamometer

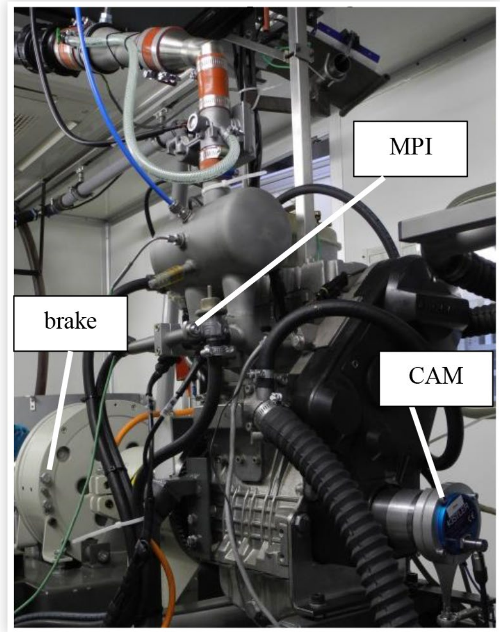


TABLE 1 Engine specification Lombardini LGW523

Engine specification		
Manufacturer		Lombardini
Type		LGW 523
Cylinder		2 in-line
Displacement	[dm^3]	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

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).

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

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.

Lubricant

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

Table 3 shows the available data of this lubricant.

TABLE 2a Fuel properties of the test fuels

specification		RON 95	n-Butanol
Other name		Gasoline, Bu0	1-Butanol
Formula		-	$C_4H_{10}O$
Density	[kg/dm³]	0.737	0.806
Stoichiometric AF-ratio	[kg air]	14.70	11.10
Lower heating value	[MJ/kg]	42.70	33.12
O_2 fraction	[$\%_m$]	1.70	21.62
Boiling range	[°C]	38-175	118
Blending RON		95	99
Blending MON		87	84
Self-ignition temperature	[°C]	300	343
Flash point	[°C]	<-40	34
Viscosity @ 40°C	[mPa*s]	0.83	2.90

TABLE 2b Fuel properties of the test fuels

specification		Bu30	Bu60	i-Butanol
Other name				2-Butanol
Formula				$C_4H_{10}O$
Density	[kg/dm³]	0.759	0.781	0.803
Stoichiometric AF-ratio	[kg air]	13.55	12.46	11.10
Lower heating value	[MJ/kg]	39.60	36.60	32.92
O_2 fraction	[$\%_m$]	8.08	14.10	21.62
Boiling range	[°C]			99
Blending RON				105
Blending MON				91
Self-ignition temperature	[°C]			
Flash point	[°C]			30
Viscosity @ 40°C	[mPa*s]			3.00

TABLE 3 Data of the utilized engine lubricant.

Property		MOTUL 300V
Viscosity grade		SAE 20W-60
Density	@ 20°C [kg/dm³]	0.867
Viscosity	@ 40°C [mm²/s]	168.3
Viscosity	@ 100°C [mm²/s]	23.8
HTHS viscosity	@ 150°C [mPa*s]	6.3
Pour point	[°C]	-39
Flash point	[°C]	238

[source: data of manufacturer]

Test Methods and Instrumentation

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.

FIGURE 2 Measuring set-up on engine dynamometer

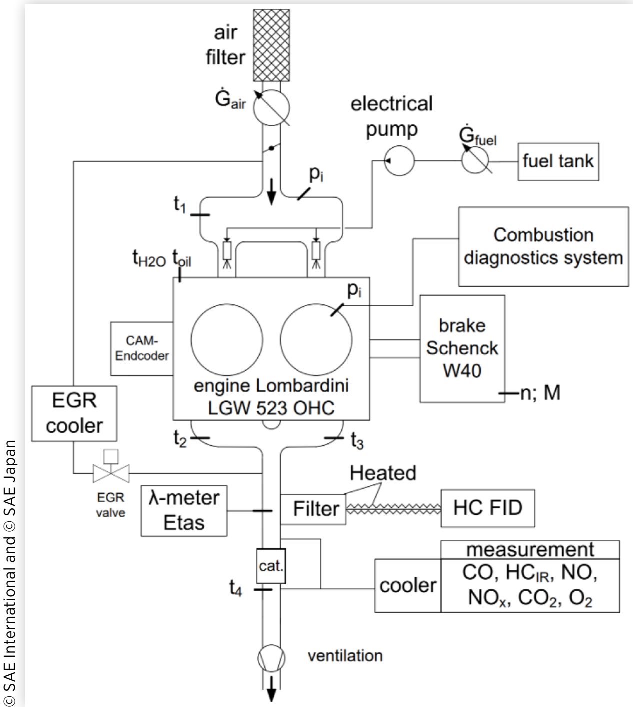


TABLE 4 Laboratory equipment used for tests.

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

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 CO_2-measurement in exhaust and intake of the engine.

Table 4 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.

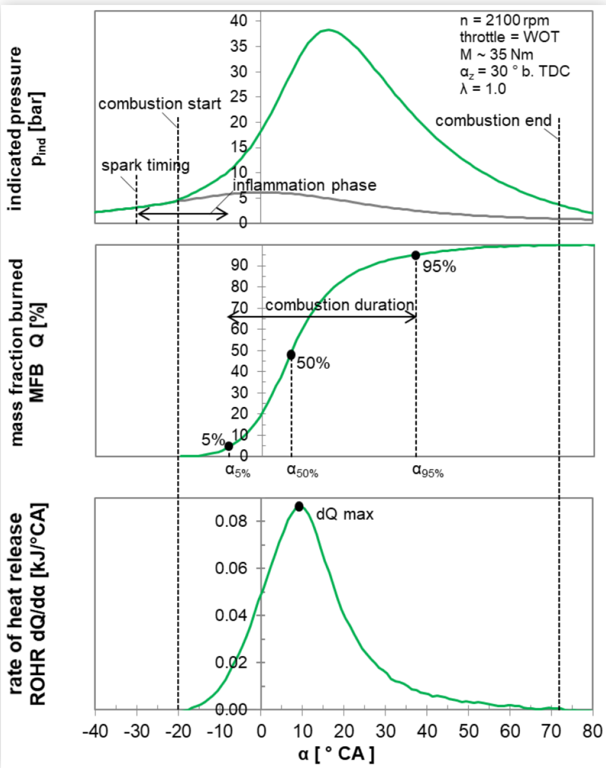
Test Equipment for Regulated Exhaust Gas Emissions

The gaseous components CO_2, CO, HC_{IR}, NO_x, O_2 were measured with analyzers Horiba VIA-510 and HC_{FID} was measured with Testa FID 123 with heated line.

TABLE 5 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 resolution 1°CA
Combustion Analysis	Datac compact

FIGURE 3 Indicated pressure and heat release



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.

Fig. 3 gives an example of indicated pressure and of heat release, which are analyzed at all operating conditions of the engine.

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 6.

FIGURE 4 Engine map of the Lombardini LGW523 engine and tested OP's

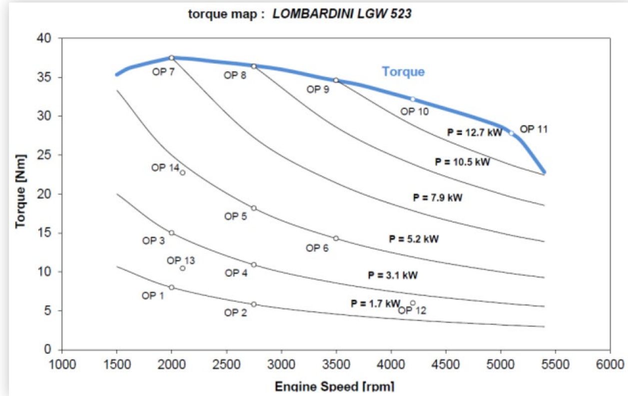


TABLE 6 description of OP's

OP	n [rpm]	M [Nm]	p_{me} [bar]	
1	2000	8	2.0	Part load
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	Full load
8	2800	36	9.0	
9	3500	35	8.6	
10	4200	32	7.1	
11	5100	28	6.0	

Results

Variations of Spark Timing αz

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, all at λ ≅ 1. 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:

- small effect on CO at low load, increased CO at higher load,
- lowering of HCFID,
- no effect on NOx at low load, clear reduction of NO_x at higher load especially with nBu100,

FIGURE 5 Comparison of emissions with different fuels during spark angle variation @ partial load

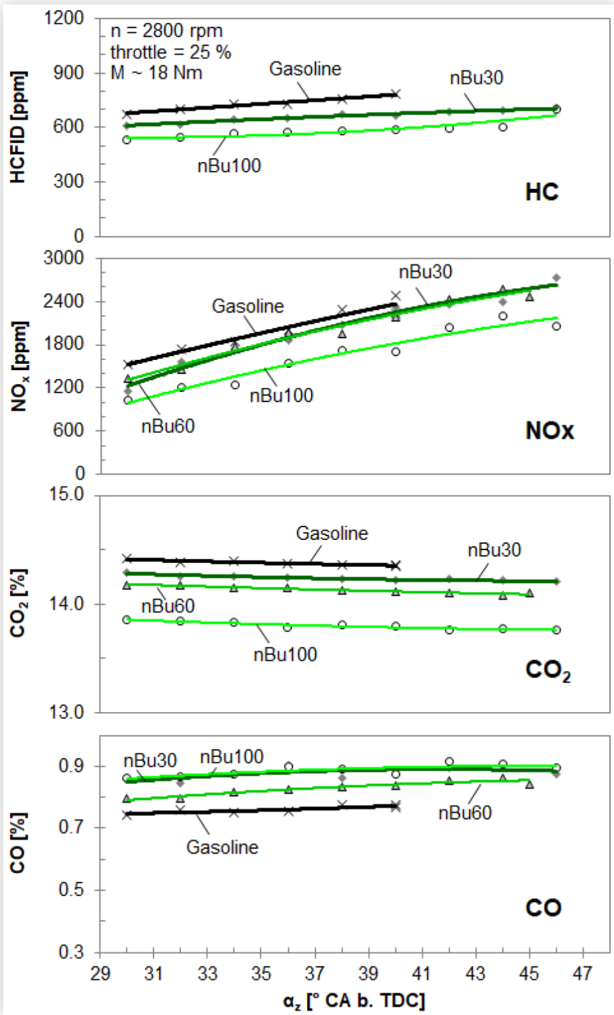
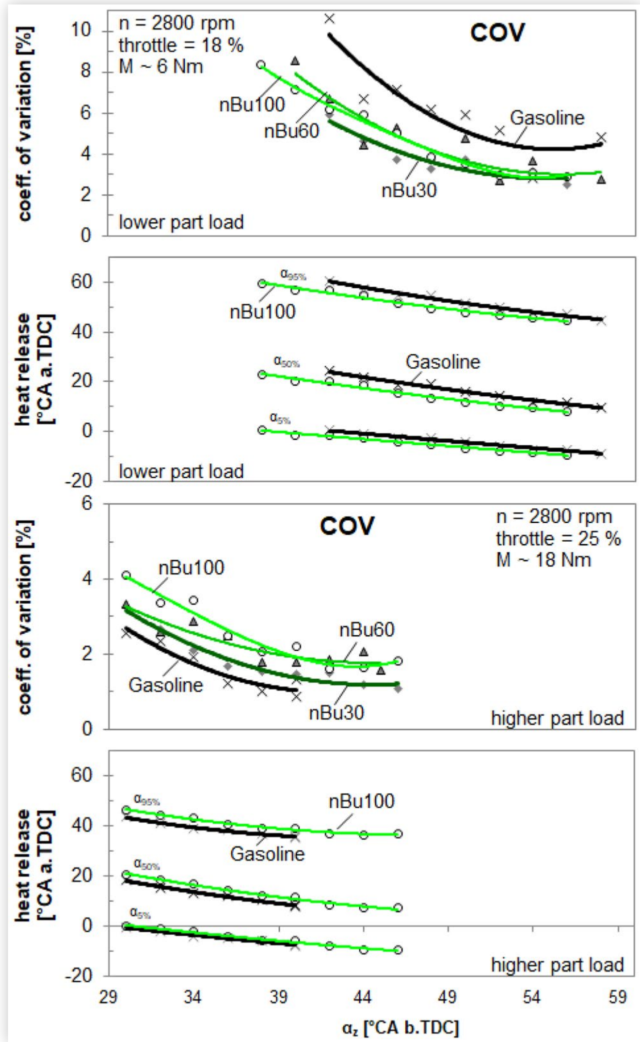


FIGURE 6 Comparison of coefficient of variation & heat release during spark angle variation @ lower & higher part load



- lowering of CO_2,
- αz for α50%@9°CA a.TDC generally later for BuXX,
- lower cyclic irregularities, quicker combustion and higher pmax at low load, inversely at high load.

For comparisons: nBu100 → 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 (IP), combustion duration, COV and pmax.

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 ($\alpha_{z\ opt}$) 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 (IP). These effects of improved combustion are more pronounced at OP1 (lowest engine speed & torque) than at higher OP4 and OP6.

Variations of Lambda λ

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.

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: λ = 1.10 - 1.15

at OP4: λ = 1.15 - 1.20

at OP5: λ = 1.25

The reason for this tendency is the lowering of the internal residual gas content with the increasing engine load.

FIGURE 7 Emissions during Lambda variation @ low partial low

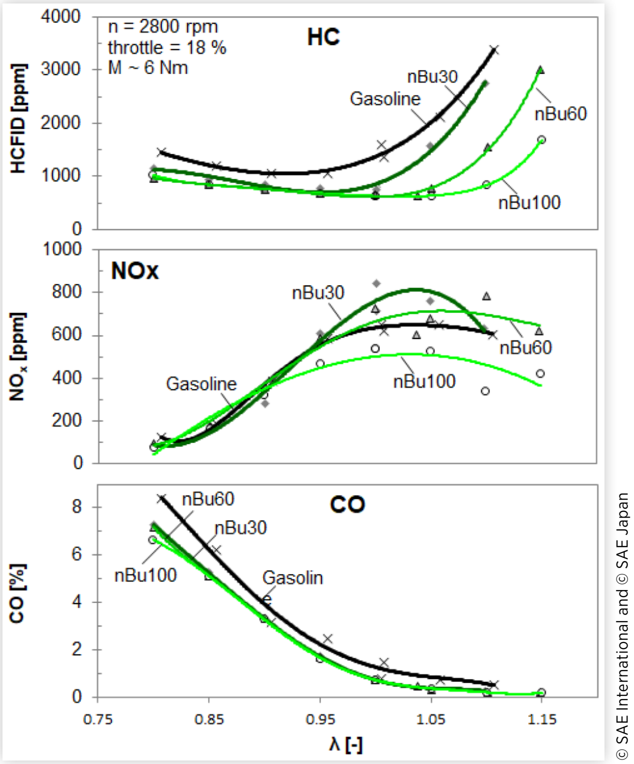
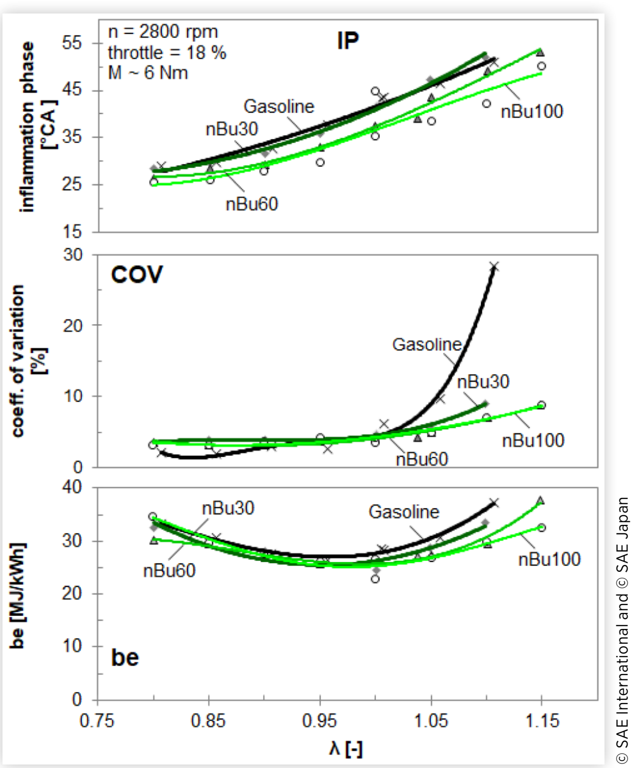


FIGURE 8 Combustion & specific energy consumption during Lambda variation @ low partial load



The diagrams of results in function of λ 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 $\lambda \cong 1.10$ and α_{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 λ-values and it has positive influences on lowering NOx and HC.

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.

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, NO_x 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.

Light-Off and Conversion Efficiencies of the 3WC

For the investigations, a TWC with metal support, EMITEC 400 cpsi, Pd/Rh = 14:1 was used.

The catalyst was fixed in the exhaust system of the engine by means of quick-assembling flanges.

To eliminate the dispersion of results originating from different cold starts the engine was warmed up without

FIGURE 9 Emissions during EGR Variation @ partial load

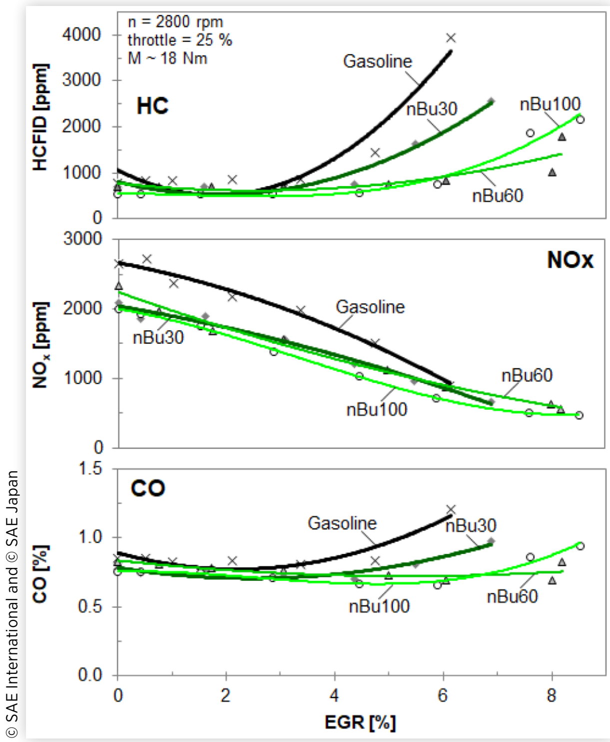
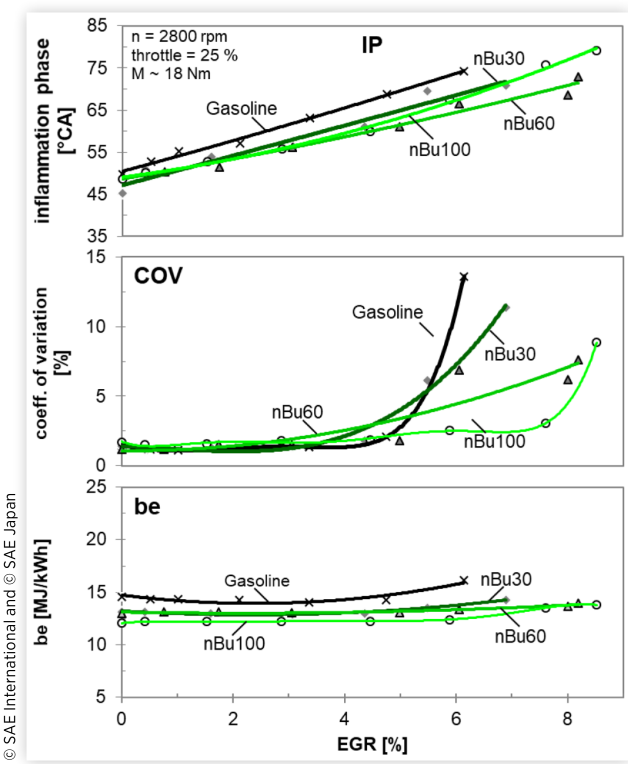


FIGURE 10 Combustion & specific energy consumption during EGR variation @ partial load



catalyst, then the cold catalyst (ambient temperature) was mounted and a new engine start was performed. The engine stop time was always 6 min and so the procedure of engine warm start, but with a cold catalyst was strictly repetitive.

In order to express the conversion rates of emission components over time, the same test was performed without catalyst mounted.

An exemplary comparison of diagrams with catalyst and without catalyst (both not represented here) allows the remarks about the principal effects of the mounted TWC: with catalyst, after approximately 3 min from the engine start, the light-off is visible as a sudden reduction of CO, HC & NO_x. After around 6 min the T_{after} TWC increases over the level of T_{before} TWC as a result of the catalytic activity and exothermic heating (not represented here).

Without catalyst, all those effects are not present.

Fig. 11 shows the plots of conversion rates K_x over time. It is not possible to find a clear and unified trend, but there is a tendency of shorter light-off time for HC and longer light-off time for CO with higher BuXX. For K_{NOX} there is no clear tendency concerning light-off time, but the fact, that for Bu60 and Bu100 only lower K_{NOX}-values are reached, confirms the interference with λ-regulation at this OP.

At OP4 (2800 rpm/11Nm) the frequency and amplitude of Lambda tension was varied by means of the ECU.

Fig. 12 summarizes the average conversion efficiencies with the six most probable variants of λ-tension signal.

It can be remarked, that with increasing Bu-content in fuel there is a slight increase of conversion efficiencies for CO and for HC, but no influence on K_{NOX}.

The use of isoButanol makes, in this respect, no differences comparing with nButanol.

FIGURE 11 Light-off of a cold TWC with different BuXX

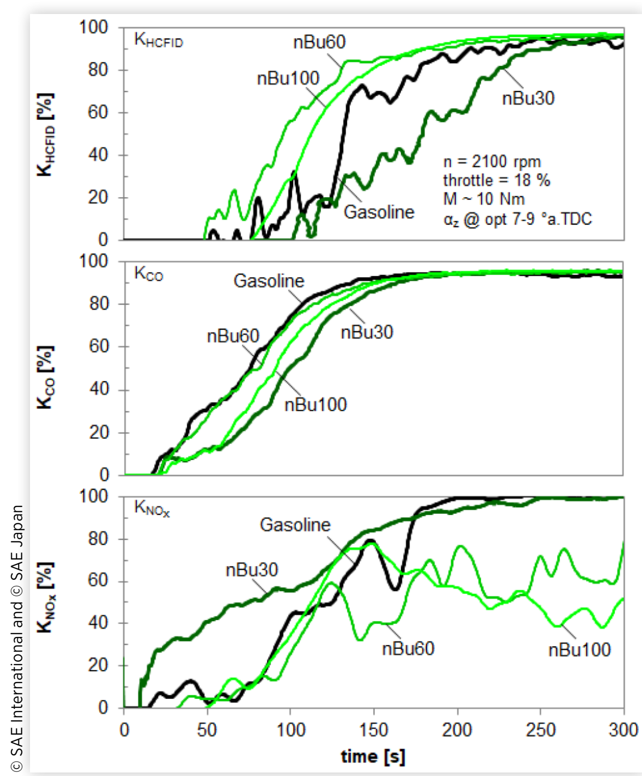


FIGURE 12 Average conversion efficiencies with different blend fuels

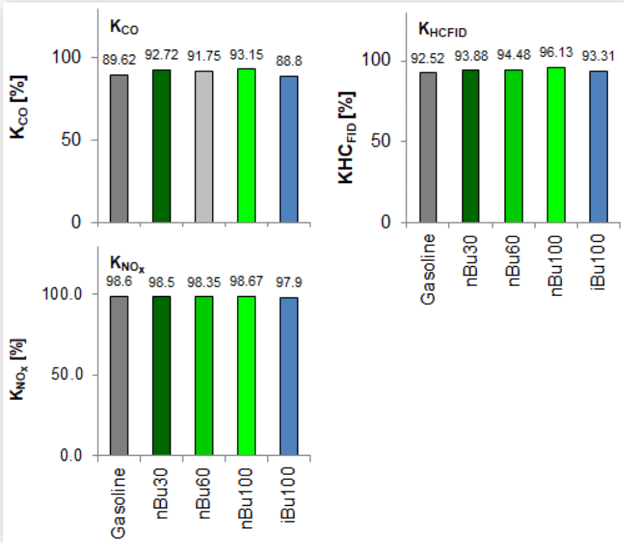
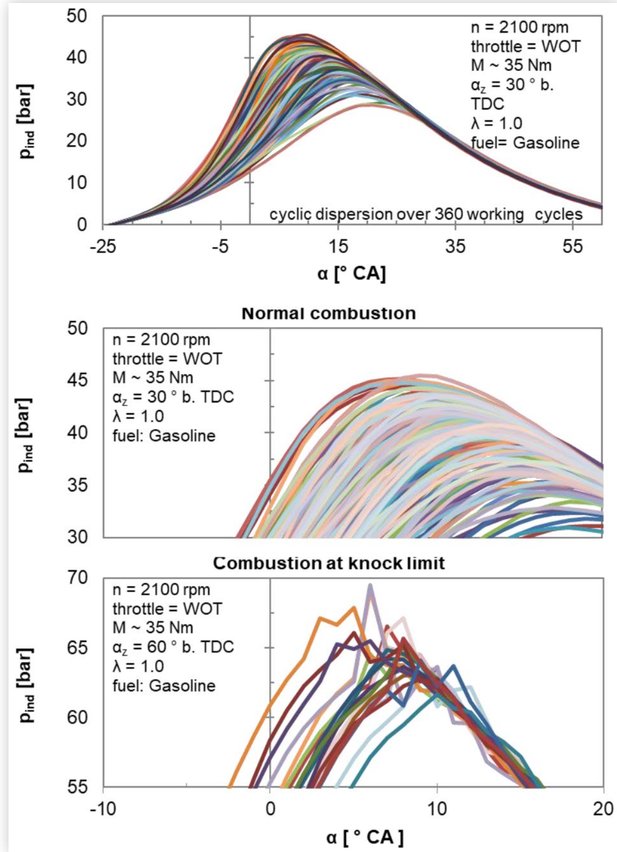


FIGURE 13 Examples of knocking cycles



Knocking

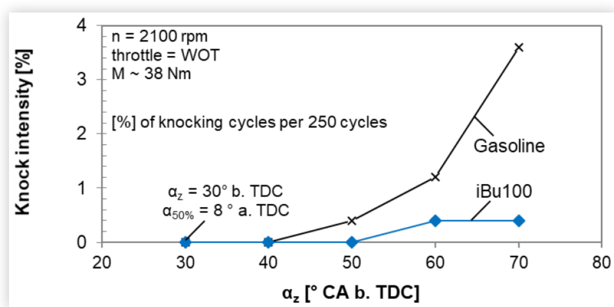
The objective of this part of tests was to confirm the potentials of iButanol (with higher RON) concerning knocking. It was necessary to approach slightly the knock limit and indicate the knocking with a very low intensity to avoid damaging the engine. The chosen OP was WOT at 2100 rpm with variation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

Fig. 13 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/dα) or with ROHR (dQ/dα) are applied. The second one, according to [2], was applied in the present tests.

Fig. 14 confirms the advantages of iBu concerning knocking: advancing spark timing (α_z) the very weak knocking starts to be recognized with iBu at α_z, which is more than 10°CA b.TDC earlier than with gasoline. Until the end of α_z-variation range (70°CA b.TDC) the knocking with iBu stays very weak ($K_i = 0.4\%$), while with gasoline the knock probability increases (up to $K_i = 3.6\%$). 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 14 Comparison of knock behavior with different fuels



Conclusions

The most important detailed 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 α_z-variations at part load of the engine show lowering of HC, NO_x & σpmi 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 NO_x values than nButanol, the time-development of

combustion is affected by isoButanol, in the same way as by nButanol.

- The λ-variations at part load of the engine show lowering of HC, NO_x & 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 λ-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 TWC light-off it is not possible to find a clear and unified trend, but there are mostly signs of retarded light-off with the highest Butanol content.
- In the operation with 3WC and λ-regulation there is a little influence on conversion efficiencies (K_x) with increasing Bu-content in fuel.
- Concerning knocking: the use of iBu moves the knock limit at FL to the higher values of spark advance.

Generally, a lower blending ratio of Butanol brings advantages at lower part load. This is mainly due to a higher Oxygen availability at local scale during inflammation and combustion. At higher engine load and/or with higher Butanol content the advantage of higher O_2-availability is compensated by effects, which slower the inflammation or produce more cyclic dispersion. These effects can originate from the higher evaporation heat and from the narrow boiling range of the higher amount of alcohol. Such influences were found in a basic investigation of [11] for Ethanol blend fuels.

Acknowledgements

The authors want to express their gratitude to the institutions, which financially supported these research activities: Swiss Federal Office of Energy (BfE), Swiss Federal Office of Environment (BAFU) and Swiss Oil Association (EV).

References

1. Brassat, A., Thewes, M., Müther, M., and Pischinger, S., “Massgeschneiderte Kraftstoffe aus Biomasse für Ottomotoren,” MTZ 12, 2011, 988.
2. Marchitto, L., Mazzei, A., Merola, S.S., Tornatore, C. et al., “Optical Investigations of Combustion Process in SI and CI Engines Fuelled with Butanol Blends”, *TAE Technische Akademie Esslingen, 9th International Colloquium “Fuels”*, Jan. 15-17, 2013.
3. Irimescu, A., Tornatore, C., Merola, S.S., and Valentino, G., “Integrated Diagnostics for Combustion Investigation in a DISI Engine Fueled with Butanol and Gasoline at Different Load Settings,” *TAE Technische Akademie Esslingen, 10th International Colloquium “Fuels”*, Stuttgart/Ostfildern, Jan. 2015, S. 117.
4. Tornatore, C., Marchitto, L., Valentino, G., Corcione, F.E. et al., “Optical Diagnostics of the Combustion Process in a PFI SI Boosted Engine Fueled with Butanol-Gasoline Blend,” *Energy* 45(1):277-287, 2012, doi:10.1016/j.energy.2012.03.006.
5. Merola, S., Tornatore, C., Marchitto, L., Valentino, G. et al., "Experimental Investigations of Butanol-Gasoline Blends Effects on the Combustion Process in a SI Engine," *International Journal of Energy and Environmental Engineering*, 2012, ISSN:2251-6832, doi:10.1186/2251-6832-3-6.
6. Szwaja, S. and Naber, J.D., “Combustion of N-Butanol in a Spark-Ignition IC Engine,” *Fuel* 89(7):1573-1582, 2010, doi:10.1016/j.fuel.2009.08.043.
7. Gu, X., Huang, Z., Cai, J., Gong, J. et al., “Emission Characteristics of a Spark-Ignition Engine Fuelled with Gasoline-N-Butanol Blends in Combination with EGR,” *Fuel* 93:611-617, 2012, doi:10.1016/j.fuel.2011.11.040.
8. Dernotte, J., Mounaim-Rousselle, C., Halter, F., and Seers, P., “Evaluation of Butanol-Gasoline Blends in a Port Fuel-Injection, Spark-Ignition Engine,” *Oil Gas Sci Technol - Rev IFP* 65:345-351, 2010, doi:10.2516/ogst/2009034.
9. Vojtisek-Lom, M., Pechout, M., and Mazac, M., “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, 2013, doi:10.4271/2013-24-0102.
10. Soloiu, V., Duggan, M., Harp, S., Vlcek, B. et al., “PFI (Port Fuel Injection) of N-Butanol and Direct Injection of Biodiesel to Attain LTC (Low-Temperature Combustion) for Low-Emissions Idling in a Compression Engine,” *Energy* 52:143-154, 2013.
11. Salenbauch, S.T., Storch, M., Hain, D., Hartl, S. et al., “Does Ethanol Always Reduce the Particulate Emissions in Gasoline Engines? - A Combined Numerical and Experimental Study in a Transparent Engine to Unravel the Cause-and-Effect Chain for E0 to E85,” Institute of Internal Combustion Engines and Thermodynamics, Graz University of Technology, *15th Conference “The Working Process of the Internal Combustion Engines”*, Graz, Sept. 24-25, 2015.

Definitions/Abbreviations

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

CO_2 - carbon dioxide

COV - coefficient of variance
dQ/dα - ROHR, rate of heat release
EGR - exhaust gas recirculation
EV - Erdölvereinigung
E85 - Ethanol 85% v
FL - full load
FID - flame ionisation detector
GasBut - Gasoline Buthanol project
GDI - gasoline direct injection
HC - unburned hydrocarbons
H_u - lower heat value
IMAP - intake manifold pressure
IP - inflammation phase α_z until 5% heat release (see Fig. 3)
K_i - [%] of knocking cycles, knock intensity
K_x - conversion (reduction) efficiency of the component "X"
L_{st} - 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
N_2 - nitrogen
NO - nitrogen monoxide
NO_2 - nitrogen dioxide
NO_x - nitric oxides
OP - operating point
p_{max} - maximum cylinder pressure
p_{me} - b.m.e.p (brake mean effective pressure)
p_{mi} - mean indicated pressure
ROHR - rate of heat release
RON - Research Octane Number
$sdev_{pmi}$ - standard deviation of mean indicated pressure
SI - Spark Ignition
t_{Exh} - temperature measured near λ-Sonde
throttle - throttle opening rate
TDC - top dead center
TWC - three way catalyst
WOT - wide open throttle
$\alpha_{50\%}$ - crank angle of 50 % heat release
α_{fkp} - α first knocking peak (on the pi-signal)
α_{pmax} - crank angle of p_{max}
α_z - spark angle
Δ_{pmax} - max. rate of pressure raise
σ_{pmi} - standard deviation of mean indicated pressure
α_{zopt} - optimum spark timing [deg. CA b. TDC] for the best torque
λ - air excess factor (m_{air} / m_{air} stoichiometric)
3WC - three way catalyst

ISSN 0148-7191