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E-FUEL BLEND OPERATION OF SMALL INDUSTRIAL SI-ENGINES WITH CARBURETORS

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Abstract: Intentions for replacing small SI-engines in motor-equipment for professional gardening and forestry by battery-electric solutions are limited by requested disposability and tolerable power-to-weight ratio. Due to this fact experimental investigations for using methanol/ gasoline fuel-blends and pure methanol in a small air-cooled industrial SI-engine (4 kW @ 3600 rpm) were carried out. At a first step (only) for these experiments, the serial mechanical carburetor was additionally equipped with a self-developed electronic lambda-control, to enable tests for different fuel-blends (Super E5, M30, M60, M100) with constant boundary conditions during engine operation without exchange of carburetor jets. This concept of control will be presented. Special needs for these SI-engines (exhaust-gas temperature, non-electric start) require a permanent sub-stoichiometric operation. For serial applications free of electronic components, the size of jets would have to be adapted as well as the use of standardized fuel-mixtures will be necessary. In addition to reference tests on different days in operation with gasoline ´Super E5´ to check repeatability, operating values and emissions will be presented for operation with the fuel-blends described. Pressure indications allow statements for changes in heat release and - additionally to acoustical perception - evaluations of combustion stability. Following inspection of engine components showed consequences of sub-stoichiometric combustion of methanol-fuel-blends and resulting recommendation. Lube-oil analysis, afterwards carried out by ATR spectroscopy shows possible contamination inside crankcase. Optical inspections and material measurements at normally used serial components of fuel system (float, housing, sealings, hoses) showed possible incompatibilities with this alcoholic fuel-blends as well as necessary alternative materials.

Key words: SI-engine, gasoline Super E5, e-fuel, fuel blend, methanol, electronic carburetor, chemical resistance

1. PROJECT MOTIVATION

The currently favorized electrification of all kinds of power drives, mainly caused by CO_2/climate-discussions reaches its technical limit in all economic sectors with restricted time frames, such as construction, agriculture, commercial gardening or forestry. The reasonably energy reservoir, stored in available accumulator technologies (e.g. 35 min for Husqvarna 120i) as well as their necessary time for re-charging (e.g.130 min for Husqvarna 120i) are no meaningful alternatives compared to the small, air-cooled SI-engines, used up to now.

The difficulties regarding manageable power-to-weight ratios, especially for hand-operated working equipment (chain saws, brush cutters, concrete cutters) and their influences on labor physiology are rarely discussed. Even well working and fuel-economy attractive 4-stroke engines with mix-lubrication [1] [2] failed inside professional market due to enlarged weight ratio of approx. 20 % compared to power-equivalent 2-stroke engines. This example significantly shows the extreme sensibility of professional customers regarding mass of their power equipment, which often must be handled in piece-rate contracts over a time of 8 hours per day.

Fig. 1a shows the nominal power rating versus the mass of commercially available chain saws in model year 2023. Data were collected from different websites (www.vergleich.org, www.amazon.de, www.baywa.de). Power rating for accumulator operated devices is often given with ‘depending on accu-level’, so that a reasonable evaluation becomes difficult. But even with the comparison of masses of cable-electric and 2-stroke saws it is obviously, that the available margin for the additional masses of accumulators is quite small.

Diagrammed in Fig. 1b are the outputs and times for use and recharging commercially available accumulator-powered lawn mowers of a Swedish supplier (www.husqvarna.com). For these times given in Fig. 1b the accumulators with the highest available capacity and the strongest re-charger were used. Power rating and usable time are not sufficient for objects with more than 1000 m^2. Comparable models of competitor Stihl are suggested for lawn areas of approx. 300 m^2… 800 m^2, so that even for ambitious hobby gardeners these devices are no meaningful options.

Alternative fuels for the existing SI-engine technology can be a wise solution for the conflict of politically driven CO_2-demands and applicability in real life. Beside biological-based alcohols with all their problems regarding monocultures electrical power-based synthetic fuels are discussed. The often favorized use of hydrogen or ammonium for energy storage fails in that case even by practical considerations regarding pressurized storage tanks and its necessary thickness of housing, so that the use of fuels, which are liquid at normal pressure and ambient temperatures, is inescapable. Even in case of a restricted volumetric energy content refilling can be executed fast, nearly everywhere without special equipment and with respect to normal safety instructions without any special knowledge.

Meaningful options can be short-chain alcohol or their blends

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with conventional crude oil-based gasolines or synthetic ones. For health effects as well as its specific energy content the use of longer-chain alcohol would be wise. But its production requires much electrical power, so that the focus is currently on methanol, which lower heating values is as half as for gasoline and its high toxicity occurred by resorption via respiration, eupepsia and skin-surface.

As a result of these preliminary consideration, the focus of a research project was set to experimental investigations on a typical small industrial SI-engine regarding the use of methanol/gasoline-blends. With special respect to financial limits and staff-potentials of a small university it was decided, to carry out these experiments for fuels with only 3 special volumetric methanol-fractions of 30 %, 60 % and 100 % (M30, M60, M100). For reference measurements and for blending component a commercial gasoline with 5 vol.% ethanol (Jet- Super E5 acc. DIN EN 228) was used.

Beside the operation and relevant operational values, the exhaust gas emissions were considered as well as the influence on the dilution of lubrication oil and material compatibility with plastics, used for standard tanks, carburetor-components and fuel lines. Cylinder-liner and sparkplug were inspected after the experiments. Practical relevance for the commercial use of these e-fuel blends relates to questions of evaporation rates of fuel inside the tanks, its possible component separation and changes in blend-ratio, occurred by the partly vaporization.

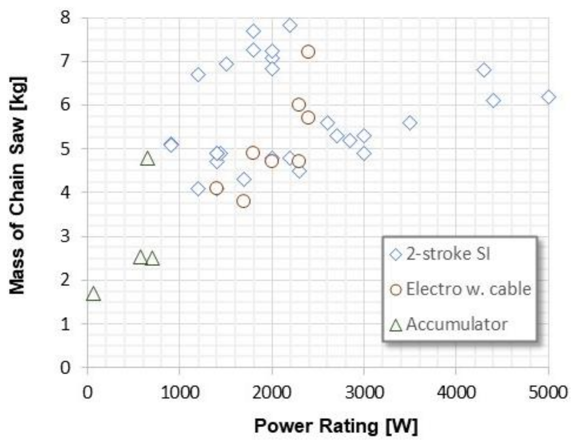

Fig. 1a. Power and mass of chain saws

Fig. 1b. Time for use/recharging of lawn mowers

2. THEORETICAL CONSIDERATIONS

2.1. Calculation of Fuel Specifications

To consider the effects of blending gasoline by methanol the relevant specifications were calculated. Due to the quite similar density of gasoline and methanol varied the values for the blends by max. 5 %, so that for dimensioning the fuel tanks the mass-related lower heating value Δh_u gives a good approximation for the volume-related energy content, too (Tab. 1). For combustion calculation the elementary analyses of all fuel-blends used, had to be calculated by mass-related superposition of both single fuels. For these calculations the fuel data for gasoline Super E5 were taken from [3]. The elementary analysis of pure methanol M100 was calculated by its molecular formula and the relevant molar masses of carbon, hydrogen and oxygen.

Tab. 1. Analysis of Gasoline (E5) and Blends with 30, 60 and 100 vol.% CH_3OH (M30, M60, M100)

Fuel	Elementary Analysis c_K [m%]	h_K [m%]	o_K [m%]	Atomic Fraction C : H : O	RON (approx.)
Super E5	88.307	11.329	0.364	1 : 1.53 : 0.00	95
M30	72.497	11.714	15.750	1 : 1.93 : 0.16	99
M60	57.167	12.087	30.668	1 : 2.52 : 0.40	103
M100	37.437	12.567	49.869	1 : 4.00 : 1.00	109

Actually, for measurement of air/fuel-ratio λ the atomic fractions C : H : O for the blends used had to be known. As well as it is very time-consuming to change these values during the measurements in lambda-meter and in exhaust-gas analysis, it was decided to leave the mass-fraction of gasoline in both measuring device and calculate the exact air/fuel-ratio for lean and sub-stoichiometric combustions by methods, usable for fuels containing important rates of oxygen, while evaluating the experiments afterwards. Simultaneously, the knowledge of the composition of fuels is basic precondition for interpretation of exhaust-gas consistency.

Due to the half energy content of methanol related to gasoline the lower heating value Δh_u decreases linearly by increasing its fraction in fuel blends (Fig. 2a, top). Furthermore, the low heating value limits its energetic shares in the blended fuels. Even with a volumetric rate of 60 % methanol its energetic portion in lower heating value is below 45 % (Fig. 2b, top). With perfect combustion the energy-specific CO_2-emission decreases by only 13 %. If the methanol is partly produced by regenerative energy and/or the necessary CO_2 for production is captured from industrial exhaust-gases or ambient air the effective CO_2-emissions are more reduced. Dependent of the literature used the values for research octane-number of methanol vary between RON = 106 [4] … 108.6 [5] … 114 [6, p. 475].

From literature there is no save numeric relation for RON of fuel-blends known. An approximation with volume-share related superposition of the properties of all single components is given by [7]. To check this approximation, the resulting RON a gasoline 'DEA-Super' was calculated this way. In [8] its composition (butane 3.8 vol.%, reformate 48,4 vol.%, light crack gasoline 27.6 vol.%, heavy crack gasoline 6.9 vol.%, tertiary butyl alcohol 1.4 vol.%, methyl-tertiary butylether 11.9 vol.%), the RON of all single components with RON = 76 … 116 and the resulting RON = 97.7 of the mixture were published. The result of the volume related superposition is calculated to RON = 98.0, so that the use of this approximation for the fuel blends used seemed to be useful. Based on [7] the RON of the blends M30 and M60 were estimated and shown in Table 1.

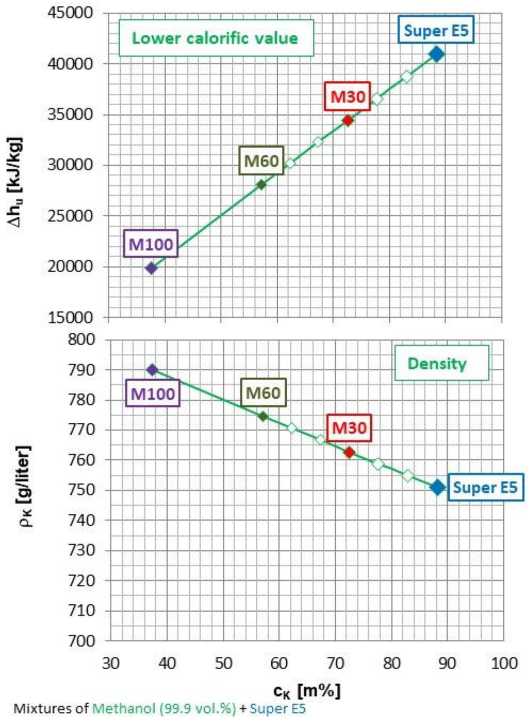

Fig. 2a. Relevant fuel specifications for blends with 0 … 100 vol.% CH_3OH

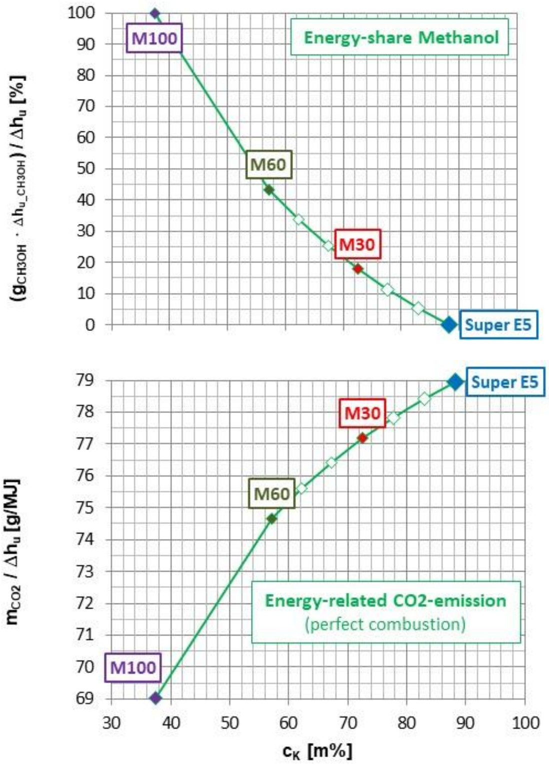

Fig. 2b. Relevant fuel specifications for blends with 0 … 100 vol.% CH_3OH

With respect to the RON = 95 of gasoline Super E5 it can be proposed that the knocking resistance of all blends will be raised. Beside this assumption the knocking resistance is irrelevant for small industrial engines, as well as the indicated mean effective pressure is quite low and this way the thermal load, too. Occurred by the special demands for starting by hand (e.g. guarantees by Briggs&Stratton) and the worldwide operation with dubious fuel qualities, hot ambient temperatures / high altitudes and inadequate maintenance at site all important suppliers (Briggs&Stratton, Honda) work with low compression ratios of ε_c = 7.5 … 8.5. Briggs&Stratton requires at least RON = 91 for their engines [9], so that every blend of gasoline Super E5 and methanol fullfills this demand.

2.2. Calculation of Water-Content in Exhaust-gas

For calculative conversion of concentrations in exhaust-gas for components measured by physical techniques according to ISO8178 in dry gas, generally for CO, CO_2, SO_2, O_2 and depending for NO_x, into output-specific mass-flows the coefficient K_{Exh} as relation between concentrations ϕ_{Exh_dry} in dry and ϕ_{Exh_wet} in wet exhaust-gas is necessary. As well as the water-steam concentration in exhaust-gas is not measured, K_{Exh} must be determined by combustion calculations, separately for lean (perfect combustion) and sub-stoichiometric conditions.

While combustion calculations for oxygen-rich mixtures are quite easy, the calculation of sub-stoichiometric exhaust-gas components becomes more complex (Fig. 3a). In these investigations the possible components in exhaust-gas were defined by only 5 components (reaction products CO_2, CO, H_2O, H_2 and inert N_2). The available content of oxygen was defined by fuel composition $C_xH_yO_z$ and air/fuel-ration λ. With 3 atomic balances for carbon, hydrogen and oxygen and a nominal oxygen-share of 21 vol.% in dry air the relevant reaction equations were formed.

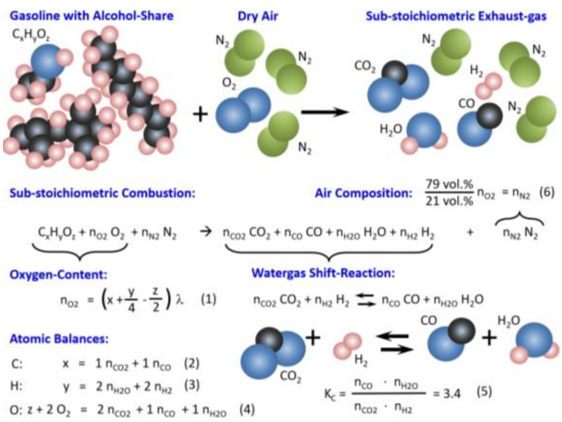

Fig. 3a. Calculation of sub-stoichiometric combustion

Watergas-shift reaction with balance factor K_C = 3.4 for frozen conditions [10] delivered the proportion of reaction products in wet exhaust-gas. A system of 6 linear equations for 6 unknown variables is the result (Fig. 3a, down), which was solved analytically. Related operations were carried out with different air/fuel-ratios λ for all fuels and blends used and diagramed in Fig. 3b.

To avoid these complex calculations for each operational point measured, a regression for operation with normal gasoline Super E5 was developed. As carried out equivalently in former investigations with gasoline/ethanol-mixtures [11] the influence of rising methanol fractions in fuels were considered by an additive regression-correction ΔK_{Exh} = f (volume-fraction ϕ_{CH3OH}, λ) to K_{Exh} for combustion of gasoline Super E5 according to Eq. 1 … Eq. 3.

For post-processing of the experimental data the λ -formular by Brettschneider [12] was used, which is also already available in the exhaust-gas analysis equipment.

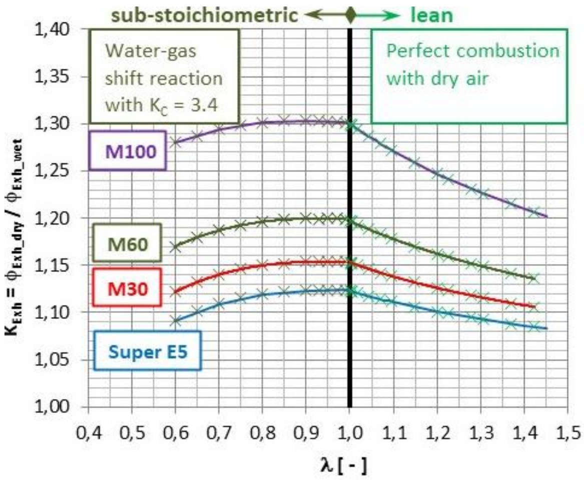

Fig. 3b. Conversion of exhaust-gas concentration

For engine operation with gasoline Super E5:

$$K_{Exh\_E5} = \begin{cases} +0.3837\,\lambda^3 - 1.2195\,\lambda^2 + 1.2797\,\lambda^1 + 0.6796 & for\ \ 0.6 \leq \lambda < 1.0 \\ -0.1364\,\lambda^3 + 0.5788\,\lambda^2 - 0.8866\,\lambda^1 + 1.5675 & for\ \ 1.0 \leq \lambda \leq 1.4 \end{cases} \quad (1)$$

Additive regression-correction for operation with methanol-shares:

$$K_{Exh_{Mxx}} = K_{Exh_{E5}} + 0.12192 \cdot \left(\phi_{CH3OH}\,[vol.\%]/_{100}\right)^2 + 0.0547 \cdot \left(\phi_{CH3OH}\,[vol.\%]/_{100}\right)^1 + 0.008 + \Delta K_{Exh}(\lambda) \quad (2)$$

with λ -correction:

$$\Delta K_{Exh}(\lambda) \begin{cases} 0 & for\ \ 0.6 \leq \lambda < 1.0 \\ (\lambda - 1)^{0.7} \cdot \left(\phi_{CH3OH}\,[vol.\%]/_{100}\right)^2 & for\ \ 1.0 \leq \lambda \leq 1.5 \end{cases} \quad (3)$$

3. EQUIPMENT FOR EXPERIMENTAL INVESTIGATIONS

3.1. Basic Test-Engine

Testbed was originally concepted for output tests of two-stroke engines [13]. Continuous problems with stability of combustion processes occurred by membrane-type carburetor while temporary operation, vibration damages at the ridged mounted engine housing and hazard for emission measurement devices avoided reasonable operation. Further the clutch supplier did not ensure the operational safety of its chosen model at engine speeds of 9300 rpm. A cage for containment safety in case of clutch failure had to be installed.

That's why the testbed was converted to performance-tests of small 4-stroke SI-engines as used for snow-throwers, portable generators, cleaning equipment or water-pumps. With the engine the exchange of clutch was necessary, too. With respect of output, spare part supply and price a Briggs&Stratton engine Intek Pro 206 was chosen (Fig. 4a). Main engine data were collected from the website of a supplier. Length of con-rod was measured at an engine grabbed out. Compression ratio was investigated while installing the sensor for cylinder-pressure indication [14].

Valve timing was measured with inductive lift-sensors several times while turning the engine by hand and averaged (Fig. 4b, down). Remarkably is the second opening of exhaust-valve during compression-stroke for de-compression in hand-start operation. After engine-start this device is disabled automatically by a mechanical ball-head-switch.

As well as the engines performance was given by manufacturer as gross-output (= brutto) according to SAE standard J1940 without attached auxiliary devices (silencer, cooling fan, ignition magnet and generator) no reliable rating value for practical use was known. Due to that fact own performance tests were carried out at testbed (Fig. 4b, top).

Fig. 4a. Test-engine Briggs & Stratton Intek Pro 206

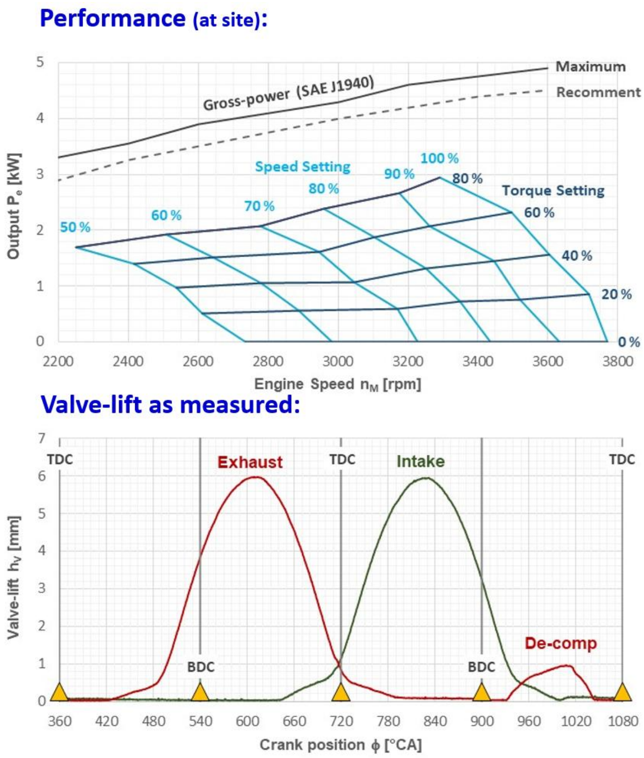

Fig. 4b. Performance at site and valve lift of test-engine

Engine performance was considered at site (approx. 22 deg C/1000 mbar) with all auxiliary devices necessary [15]. Output measured at testbed is not necessarily performance-maximum of this engine type as well as the supply voltage for the electric retarder was limited to BES = 29 V. Torque setting of the retarder was interrupted at 80 % of maximum because with settings of the speed-governor lower than 70 % no stable engine operation was possible anymore.

Remarkable is the strong speed droop, the mechanical speed-governor provides. While a speed drop of $\Delta n/n_M$ = +3 % between full and zero load is standard for large diesel-gensets this SI-engine does not reach its nominal speed n_N = 3600 rpm already at torque settings of 40 %.

3.2. Conceptions for Adjustable Air/Fuel-Mixtures

Even without any experimental investigations in methanol operation and with the experiences in ethanol-operation [11] it became clear, that mechanical carburetors must be adapted for the use of oxygen-rich fuels, as well as the air/fuel-ratio λ would reach the lean limit for misfiring. Already in earlier projects concepts for adjusting the air/fuel-ratio for SI-engines with mechanical carburetor were investigated.

Based on the basic layout four different strategies were identified. Without changing the sub-stoichiometric sizing of the fuel's main-jet (= calibrated main fuel metering orifice [16]) the easiest way seem to be systematic addition of secondary air ("fault-air") after throttle of the carburetor (Fig. 5a, top).

Pressure in intake manifold of natural aspirated SI-engines is below ambient pressure, so that no flow-supporting device would be necessary. With an easy metering-valve the amount of secondary air can be adjusted from basic air/fuel-ratio λ = 0.7 to the lean limit of ignition. Experimental considerations showed that the pressure p_{Intake} in intake manifold is not sufficiently negative for acceptable range of λ -variation [14].

A second way for in-operation variation of air/fuel-ratio with sub-stoichiometric basic layout would be the use of a pulsed solenoid valve in fuel line before carburetor (Fig. 5a, down). Due to the non-available solenoid valve and its electronic amplifier for pulsing this option was refused. An alternative way was found while continued literature studies [17] with injecting air bubbles into the fuel line before carburetor [18]. This idea was rejected due to apprehension regarding save fuel supply for engines with fuel delivery by gravity as normally used for small SI-engines.

With lean basic layout the idea of a booster fuel-pump was tested. Even with a booster-pressure of 730 mbar no relevant change in air/fuel-ratio was measured (Fig. 5b, top). The addition of this fuel pump did not influence the operation of the float chamber.

With these preliminary studies [14] [17] [19] [20] the old idea of combining lean basic layout by diameter-reduced fuel-jets and adjustable choking device for combustion air [21] [22] was reanimated (Fig. 5b, down). Based on the diameter in standard main jet, several jets were manufactured with smaller diameters and tested.

Oxygen content in exhaust-gas is measured by a separate lambda-sensor Bosch LSU4.9. Its signal is converted into an analogue voltage of 0 … 5 V and transmitted to a microcontroller, which compares the measured l with the given target value. According to this control deviation the necessary position of choke (Pos_Choke) is calculated by the self-developed PID-controller software of microcontroller and adjusted by a small servomotor, driving the shaft of the choke plate.

With the finally chosen setup of main jet and flow area of choke lambda-variation in the range of λ = 0.7 … 1.2 became possible in gasoline-operation.

With a test of fuel-switch from normal gasoline Super E5 to fuel-blend M60 with a content of 60 vol.% methanol the assumption of necessary in-operation adaptation of carburetor setting was confirmed experimentally (Fig. 6a). Air/fuel-ratio raised from λ = 0.75 to λ = 1.1. In combination of a carburetor layout of $\lambda \approx 0.85$ for gasoline-use and higher methanol additions a faultless operation was not ensured anymore.

Fig. 6b shows a fuel-switch from gasoline Super E5 to methanol-blend M30 with enabled lambda-control. Air/fuel ratio is set to a value of λ = 0.86, which is normal for these industrial SI-engines at part load. As shown in Fig. 6a there is a time delay of approx. 60 s of entering the blend into the float chamber in relevant quantity. Choke position increases immediately because of the lower stoichiometric air requirements of the methanol content. Air/fuel ratio is quite constant with tolerances lower than $\Delta\lambda$ = 0.05, occurred by instabilities in combustion. Because of higher evaporation enthalpy the exhaust gas temperature becomes with Δt_{Exh} = -10 K slightly lower than in gasoline combustion. With constant sub-stoichiometric air/fuel ratio the lambda-effect of hotter combustion while converging to λ = 1 is excluded.

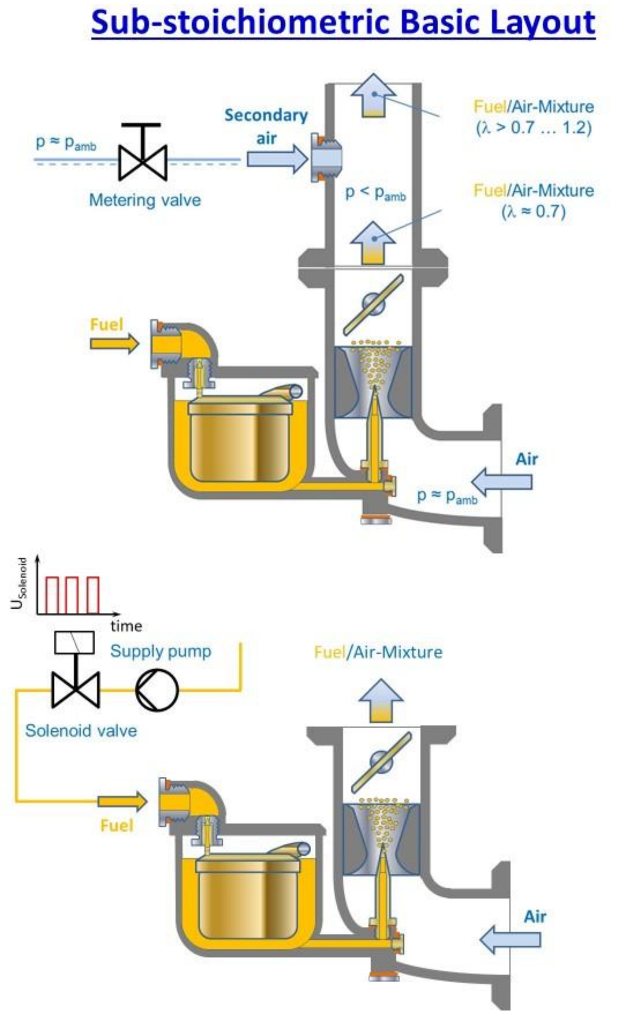

Fig. 5a. Strategies for λ-adjustment with sub-stoichiometric basic layout

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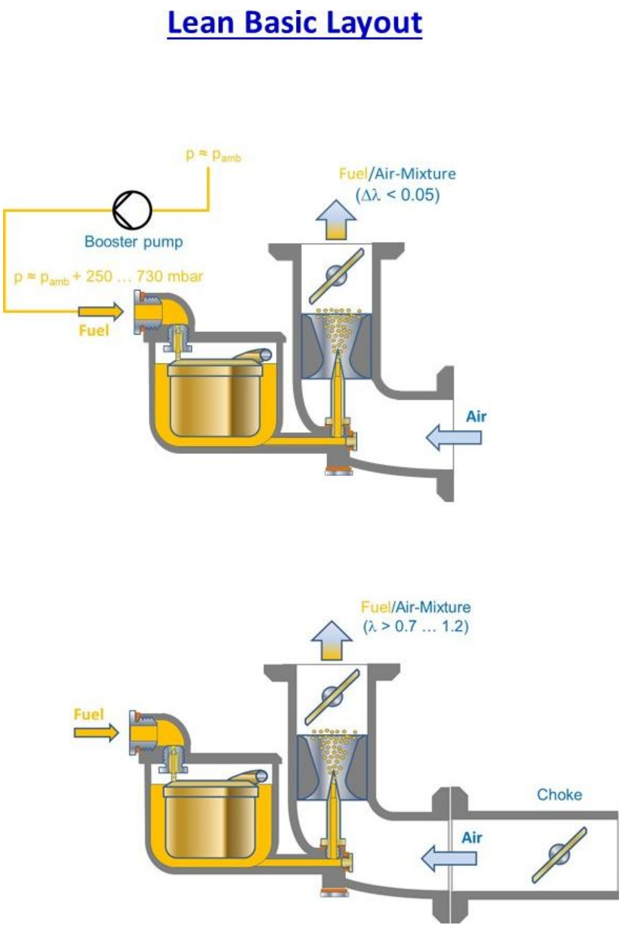

Fig. 5b. Strategies for λ-adjustment with lean basic layout

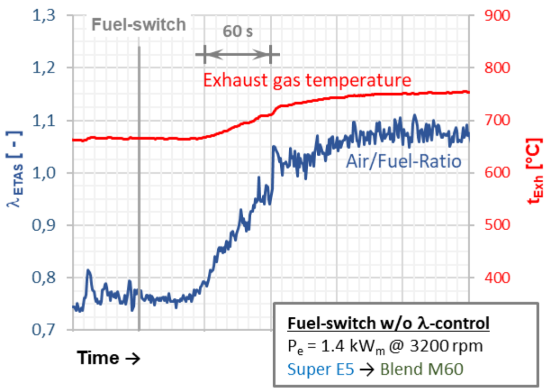

Fig. 6a. Fuel-switch without adaptations of carburetor

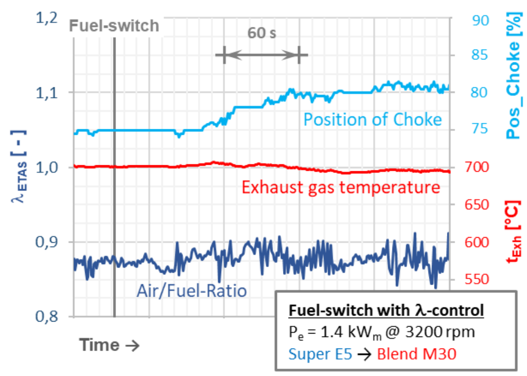

Fig. 6b. Fuel-switch with enabled λ-control

3.3. Relevant Test Equipment

Testbed is equipped with standard pressure sensors and temperature probes (NiCr-Ni, Pt100) for integral operation values of the engine and all necessary monitoring sensors for safe operation. Selection of relevant test equipment is displayed in Fig. 7.

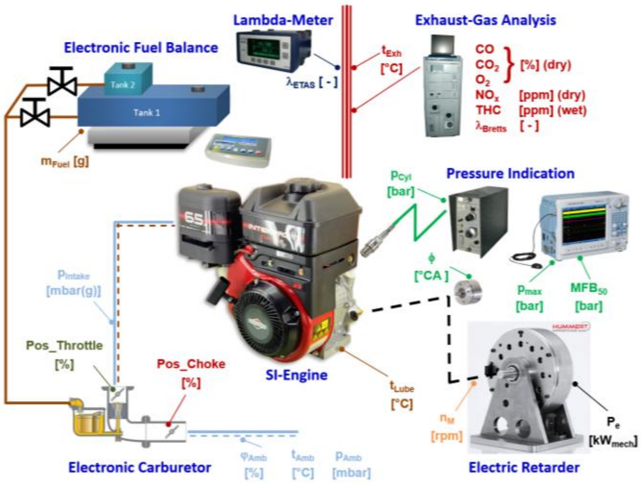

Fig. 7. Relevant test equipment

Engine itself is equipped with a mechanical speed-governor for engine speed n_M acting the throttle of carburetor. Engine speed n_M is detected by an optical sensor, observing a reflecting mark at the surface of the clutch. Position of throttle Pos_Throttle is detected by rotary potentiometer as well as the setting of choke Pos_Choke.

Tab. 2. Relevant test equipment and measuring devices

Value	Measuring principle	Type
Output P_e	Electric retarder (eddy-current)	Hummert HAT WWB C1
Engine speed n_M	Optical reflection sensor	Alborn FUA 9192
Fuel mass m_{Fuel}	Laboratory balance	Kern ITB35K1IP
Fuel/air-ratio λ_{ETAS}	ZrO_2-sensor	Lambda-Meter ETAS ES630.1 / BOSCH LSU4.2
Exhaust gas CO CO_2 O_2 NO_x THC	 NDIR NDIR MPA CLA (dry / cold) FIA	Horiba EXSA-1500
Cyl. indication $p_{Cyl} = f(f)$	Piezo-electric transducer Charge amplifier Optical encoder ScopeCorder	KIAG 6051B KIAG 5007 Hohner Serie 27 Yokogawa DL850

Additionally, the pressure inside intake manifold p_{Intake} was taken to exclude influences of fluctuating ambient pressures.

Ambient conditions (t_{Amb}, p_{Amb}, f_{Amb}) were measured inside an air-container, which can be supplied by an aircondition.

4. EXPERIMENTAL INVESTIGATIONS

4.1. Engine Tests

Engine tests were carried out on 3 different days within 4 weeks. Fuel-mixtures were prepared with pure methanol (99.9 vol. %) and commercial gasoline Super E5 (JET) with an ethanol content of max. 5 vol.%. Mixtures were blended according to calculated mass fractions and filled for the tests into tank 2 while pure gasoline was stored in tank 1. For all measurements a standard output P_e = 1.4 kW @ 3200 rpm (break torque M_d = 4.12 Nm) was used. The engine was started in gasoline operation and driven up to normal lube-oil temperatures t_{Lube} = 91 °C. After the heating-up procedure tests with variations of fuel started. Not consumed fuel-blends were removed from tank 2, while the engine was re-switched to gasoline operation from tank 1 and replaced by the next blend for testing. On each testing day reference measurements in gasoline operation (Super E5, Ref. 1 and Ref. 2 in Fig. 8, Fig. 9a-c) were carried out.

Each testing-day was ended by long-term gasoline operation from tank 2 for purging whole fuel system, as compatibility with materials of tank 2, fuel-line, sealings, jets, needle-valve, float and its chamber was not clear and became subject of additional considerations.

4.2. Experimental Results of Engine Tests

Relevant results of experimental investigations with the gasoline Super E5, the blends M30 and M60 as well as pure Methanol M100 are shown in Fig. 9a … c. Diagrammed in Fig. 9a are the operational values fuel consumption m'_{Fuel}, the specific fuel consumption $b_{e42.7}$ related to standard lower heat value of Δh_u = 42.7 MJ/kg and that way reciprocal to the efficiency and the exhaust-gas temperature t_{Exh} versus the air/fuel-ratio λ.

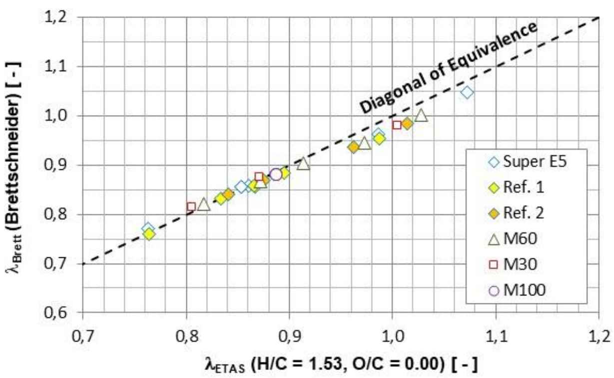

Fig. 8. Fault of Lambda-Meter without adjusting fuel-parameters

Air/fuel-ratio was measured with the lambda-meter by ETAS. Values of fuel composition H/C and O/C were set constant to the values for Super E5 and not changed during engine operation. Afterwards the results of lambda-meter were counterchecked by values calculated from complete exhaust-gas emissions by Brettschneider-regression, usable also for oxygen-rich fuels [12], with real fuel-composition. For single measured points additionally analytical calculation with all components in sub-stoichiometric combustion were carried out according to watergas-shift reaction with the balance constant K_C = 3.4. The failure of ETAS-device was approx. 1 %, related to Brettschneider-regression (Fig. 8) and 2 % related to combustion calculation within the interval of λ = 0.7 … 1.0. Diagramming versus ETAS display without changing fuel-parameters seemed to be acceptable.

Fuel consumption m'_{Fuel} rises by using e-fuels due to poor energy content compared to standard hydrocarbon-fuels. Tank volume capacity must be enlarged by approx. 75 % to ensure same operating range (Fig. 9a). Surprising is the energy content-related specific fuel consumption $b_{e42.7}$. As long as the methanol volume-share is below 30 % (M30) the efficiency is the same as for gasoline operation. This result can be explained by cylinder-indication (Fig. 10). Up to methanol volume-share to 30 % (M30) the heat release is nearly unchanged compared to standard operation with gasoline Super E5.

With higher methanol contents efficiency increases by three effects. First, even at same global air/fuel-ratio the oxygen content in fuel blends leads to more complete combustion due to local O_2-concentration, provided by the methanol. Concentration of unburnt components CO and THC in exhaust-gas decreases significantly (Fig. 9b). Second, due to higher local O_2-content in cylinder gas the combustion gets faster, what will be demonstrated by the cylinder-indications in Fig. 10, too. Oxygen contents in fuels enlarge the velocity of the flames during combustion [23]. The combustion process is significantly advanced by approx. 4 °CA in operation with M60 and M100. The same effect was already observed by the tests with ethanol-shares in gasoline [11].

Third, the higher evaporation enthalpie of methanol leads to lower gas temperatures inside the cylinder, what lowers the specific isochoric heat capacity of the cylinder-gases. The influence of this third effect is quite small. Cycle calculations with completly constant heat capacities at a large dual-fuel engine S.E.M.T. Pielstick 18PC2-5 DFC showed efficiency improvements lower than 5 % [24]. With pure methanol M100 the advantage in energy consumption is approx. 20 %, what does not compensate the lower content of chemical energy.

Exhaust-gas temperature becomes lower with raising methanol shares according to the standard evaporation enthalpy of Δh_{V_CH3OH} = 1100 kJ/kg @ 1013 mbar [25]. The cylinder gas mass is cooled in inlet manifold and inside the cylinder during intake stroke. Additionally, the fuel-mass burnt per cycle is approx. 75 % higher in methanol-operation, so that the temperature at the start of compression is lower than with gasoline ($\Delta h_{V\_Gasoline}$ = 380… 500 kJ/kg @ 1013 mbar [25]). The whole temperature level of the engine's process is dominated by the gas temperature at the start of compression stroke. This way exhaust-gas temperature decreases in e-fuel operation.

With lower gas temperatures inside the cylinder instable combustions were suspected. Fig. 9b shows the standard deviation of indicated peak pressures inside the cylinder. Up to volumic shares in fuel of 100 % methanol the standard deviations in peak pressures are within the tolerance of operation with pure gasoline, measured at the 3 different test-days (Super E5, Ref. 1 and Ref. 2).

Diagrammed in Fig. 9c are the mass-related specific emissions for carbon-monoxide CO, residual hydrocarbons THC from unburnt fuel and Nitrous oxides NO_x. As well as the concentrations for NO_x and CO were measured in dry exhaust gas, the measured values had to be corrected to wet conditions in un-cooled exhaust-gas by factor K_{Exh} according to Fig. 3b. Additionally, the specific NO_x

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emissions must be corrected depending on the water-content inside the combustion air at site according to ISO 8178.

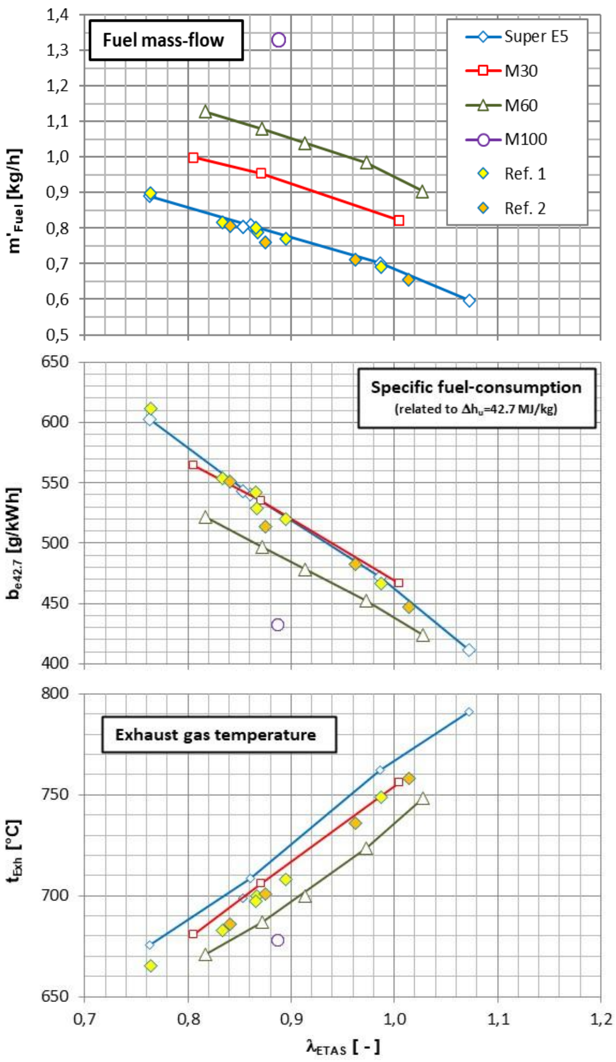

Fig. 9a. Test results – Operational values

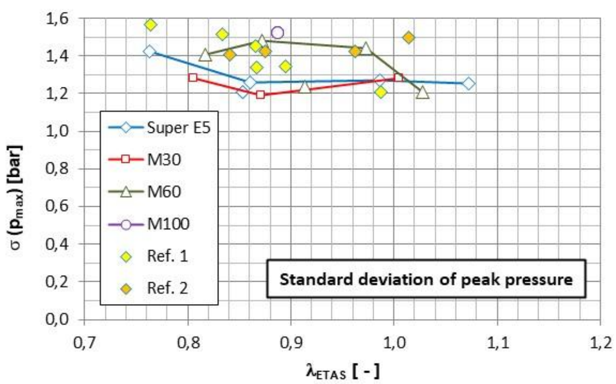

Fig. 9b. Test results – Standard deviation of peak pressure

As mentioned above, the local availability of O_2 close to the flame during combustion decreases the content of unburned components CO and THC in exhaust-gas. Significantly is the influence on specific NO_x emissions. For the formation of NO_x are high local gas-temperatures, sufficient local concentration of O_2 and time are necessary.

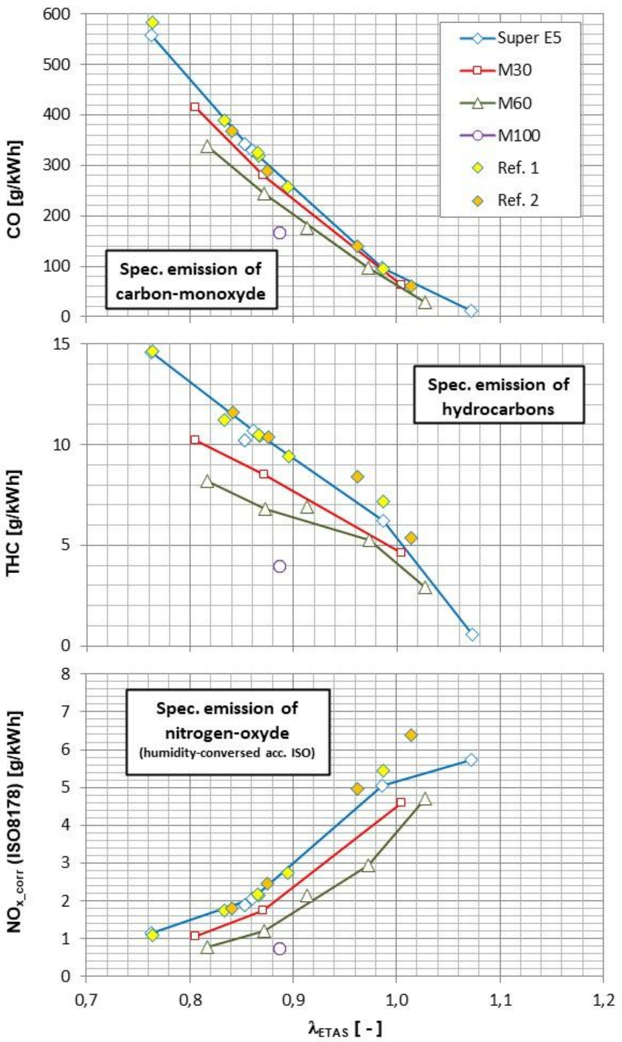

Fig. 9c. Test results – Specific exhaust gas emissions

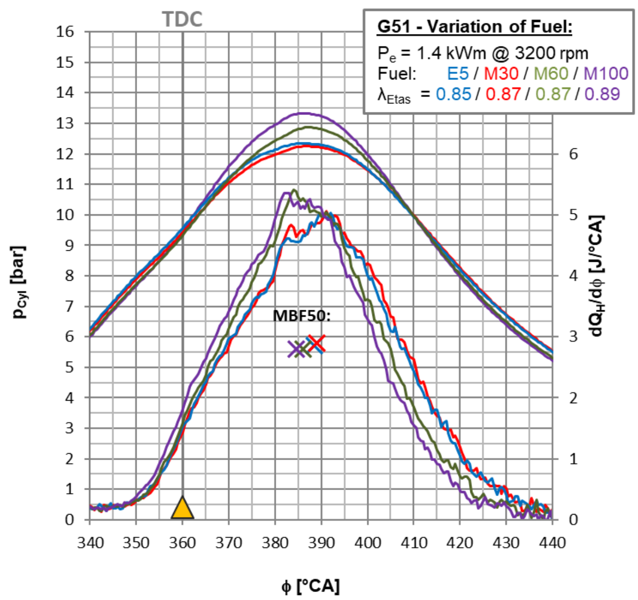

Fig. 10. Test results – Pressure indications at $\lambda \approx 0.85$

At the same operating point of the engine the influence of time is excluded. With constant rating and engine speed in that operating point a shift in ignition timing can be excluded, too. While higher O_2-concentration leads to higher NO_x-level the formation of thermal NO_x would be decreased by lower gas-temperatures. It becomes clear that the low gas-temperatures in blend-operation and with pure methanol dominate this effect as well as the level for NO_x-emissions is decreased significantly.

Cylinder indication was carried out with 100 cycles per measuring point. While post-processing it became clear, that especially at higher air/fuel-ratios with unstable combustions the recording of more cycle would have improved the results.

Based on the pressure indications carried out a slight influence on the cylinder peak pressure p_{max} can be detected (Fig. 10). Due to advanced combustion detected by the crank-angle MBF_{50} of half chemical energy released the cylinder peak pressure p_{max} was enlarged by less than 1 bar. Compared to the cycle-to-cycle deviation of more than 6 bar this small increase is irrelevant for the stability of crank-drive and cylinder unit.

5. ASPECTS OF OPERATION AND MAINTANANCE

5.1. Inspections of Engine Components

Heat rating of the sparkplug was not changed for operation with methanol/gasoline-blends. Despite concerns regarding the lower gas-temperature inside the combustion chamber and that way forming of deposits at the electrodes the original sparkplug was not replaced. Even in operation with pure methanol no anomalies in combustion cycles were detected.

Despite the lower gas temperatures inside the cylinder at compression start due to the high enthalpy for evaporation of methanol no abnormal deposits were found during the optical inspection at the electrodes of the sparkplug (Fig. 11a, photo). No changes of sparkplug configuration seemed to be necessary.

Fig. 11a. Sparkplug after methanol operation

Combustion chamber was inspected after the tests by endoscope (Fig. 11b). Deposits of lube-oil coke were detected at piston head. No cleaning effect of methanol could be observed. The upper flank of first piston ring seemed to be corroded, what is a possible effect of sub-stoichiometric combustion of alcohols, forming formic acid. In consequence to avoid further damage, sparkplug was removed after every day's test-run, cylinder was filled by fresh lube-oil and engine was turned by hand to distribute the lube-oil at the liners surface.

Fig. 11b. Endoscopy of combustion chamber [26]

5.2. Lube-oil Contamination

Fresh and used lube-oil after operation with blends and pure methanol were analyzed by ATR-spectroscopy (Fig. 12). Both spectra seemed to be quite equal. Methanol could not be detected in the ATR-spectrum. The characteristic band of the C-O stretching vibration and the OH deformation vibration at 1021 cm^{-1} is not present in the spectrum of the used lube oil. But the engine was operated after all tests with gasoline over a time-period of approx. 1 hr. for purging all fuel equipment. Possibly in this way the contamination of lube-oil with methanol could be eliminated by evaporation.

As a hint for carbonyl groups differences in spectrum were detected at the band of 1739 cm^{-1}. The carbonyl groups can be occurred by formaldehyde or formic acid. Formaldehyde seems to be implausible due to its evaporation behavior, so that probably formic acid, produced in sub-stoichiometric combustion of methanol, contaminated the lube-oil.

Additionally X-ray fluorescence examinations showed contamination with the element iron, what could be occurred by the influence of acid at cylinder liner and piston rings as described above. This observation supports the theory of acid input into crankcase. No TBN were investigated.

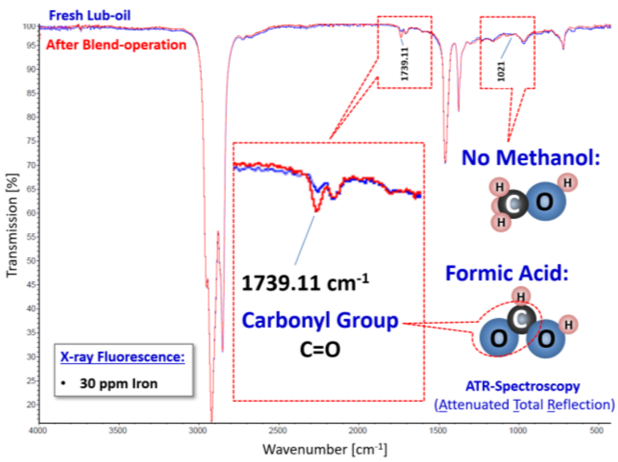

Fig. 12. Results of analysis of lubrication-oil

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5.3. Chemical Resistance of Materials

Chemical resistance of different materials used in engine components were tested with pure methanol and its blends with gasoline. Besides optical evaluations mechanical tests were carried out, too. In fact, all materials tested and used in components of the engine were chemically attacked by these fuels (Fig. 13).

Material	Chemical resistance in CH_3OH	Gasoline/CH_3OH-blends	Components
Elastomeres			
PVC rigid	✓	✓	spacers
PVC flexible	–	–	tubes, sealings
FKM	–	–	o-rings
NBR	–	–	o-rings
PA	–	–	tanks
POM	(✓)	(✓)	floats
Metals			
Zinc diecasting	(✓)	(✓)	housings
Brass	–	–	floats, throttle
AlMgSi 0,5	(✓)	(✓)	
X5 CrNi 18-10	✓	✓	

Fig. 13. Results of material tests [26]

6. CONCLUSIONS

The influence of fuel-blends of gasoline and methanol on the operational values and emissions of small industrial gasoline SI-engines was considered for one part-load operation point with constant output P_e = 1.4 kW @ 3200 rpm. Conclusions were found as follows.

Sub-stoichiometric operation of small industrial SI-engines was stable up to 100 % methanol content in fuel. No significant differences in standard deviation of indicated peak pressure were observed.

The simple exchange of conventional hydrocarbon fuel without adaption of carburetors is not possible. With respect to the oxygen-content of alcoholic share larger main-jet areas are necessary to achieve same air/fuel-ratio.

Based on the lower calorific value of methanol fuel consumption is rising nearly the same relation. Larger tanks will be necessary. Oxygen content accelerates the heat release. Efficiency at typical air/fuel-ratio λ = 0.9 is rising by approx. 7 % in operation with M60 and 17 % with pure methanol M100.

At same air/fuel-ratio λ = 0.9 emissions of carbon monoxide CO are lowered by 27 % in M60-operation and by 45 % with pure methanol M100. Due to enlarged evaporation enthalpy of methanol the NO_x-emissions are improved by 38 % and 74 %.

Sub-stoichiometric combustion of alcoholic fuels leads to formation of acids. Carbonyl groups as hint for formic acid were detected in lube-oil by ATR-spectroscopy. Optical inspection of liner and piston rings showed corrosion.

All tested elastomers and metals used normally in fuel lines of conventional carburetors were attacked chemically by methanol and its fuel blends.

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Lube-oil Analysis

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