First tests of laser ignition in Wankel engine

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Abstract. Laser ignition has been studied in powerful four-stroke engines, not only because of the fast payback, but also because of the more convenient diagnostics in a large scale setup. High-performance compact engines have not been studied, even though advantages of laser ignition could be much more pronounced for those because of harmful emission reduction and multi-fuel abilities. Compact piston engines are considered as an alternative for fuel elements and batteries for portable, automotive and unmanned aerial vehicles. These are characterized by a small combustion chamber comparable to the spark plug inter-electrode gap in axial direction, and its low ratio to bore size. However, for Wankel engines this problem exists at any scale. Laser ignition of lean fuel mixtures in such engines could significantly improve performance by reduced fuel consumption, thermal loads, and a cleaner exhaust. We have investigated the possibility of laser ignition in rotary-piston (Wankel) sub-kW scale model engine using different kinds of fuel mixtures: hydrogen, methane, propane, butane, gasoline, and ethanol based. A custom built compact diode-pumped solid state laser has been used to substitute the original glow plug, respectively. Laser ignition has been found possible and quite beneficial for both types of engines and different fuel mixtures; in terms of NOx emission reduction especially.

1. Introduction
Compact piston engines are considered as an alternative to fuel cells and batteries for portable, automotive and unmanned aerial vehicles (UAV) [1]. They are characterized by a small combustion chamber comparable to the spark plug inter-electrode gap in axial direction, and a small ratio to the bore size. However, for Wankel engines, this problem exists at any scale [2, 3]. Unlike electric spark, laser ignition energy decreases with pressure increase in a reasonable range up to cca 100 bar. Multi-point ignition could also be helpful, but is complicated to implement with electric sparks. Data regarding laser ignition in piston engines can be found mostly for four-strokes [4, 5], but, despite great potential for performance improvement, in compact two-stroke [6] and rotary piston (Wankel) engines it is still almost unstudied. For the latter, laser ignition was only suggested by Mazda in 2011, but there are still no papers regarding this problem; except constitutive patent application [7]. Recently, this company has announced Skyactiv-X compression-ignition rotary-piston technology to be used as an electrical vehicle back-up generator that will be shoe-box size, delivering low noise and vibration.

Though Wankel engines have higher volume and mass specific power, as well as a relatively simple construction and easy handling, these factors are now outweighed by high fuel consumption and harmful emissions rates. These problems could be resolved using gaseous fuel, hydrogen especially [8]. Laser ignition of lean fuel mixtures in such engines could significantly improve performance by reduced fuel consumption and a cleaner exhaust because of lower...
combustion temperature [9]. These also reduce thermal stabilization issues, which are more pronounced in compact systems. One more feature needed for portable and temporarily set engines is the ability to use multiple and locally available low-quality fuels. E.g., in remote Arctic areas natural gas is available from the ground, but gasoline and diesel is brought from industrial centers which can increase operating costs by an order of magnitude. Existing multi-fuel engines to date are mainly based on conversion of Otto and Diesel engines, but not two-stroke or rotary piston ones. So the aim of this work was a proof-of-concept for a laser ignited Wankel engine fed by different fuels.

2. Experimental setup
We used a 49-PI (O.S. Engines) Wankel model engine (figure 1). The housing for it was made to match a type F glow plug hole and the radiation was focused by a 5 mm diameter sapphire half-ball lens (48-432, Edmund Optics). A drop castor oilier for piston lubrication was attached to the intake at operation with gaseous fuels. We loaded the engine with an automotive generator coupled to an electronic load. The exhaust was fitted to an industrial gas analyzer (O₂, CO, CO₂, NOₓ, CH). Experimental stands were assembled in a fume cupboard for highly flammable media treatment.

The laser spark plug [10] is based upon a monolith Cr:YAG passively Q-switched (25% initial transparency) end diode-pumped Nd:YAG crystal (6 mm diameter, 15 mm length, 1 at % doped) with resonator mirrors sputtered at the edges (45% output reflection, custom manufactured by Alphalas; YAG—yttrium aluminum garnet, Y₃Al₅O₁₂). A fiber-coupled 50 W diode laser (FL-FCSB04-50-808, Focuslight) was driven by LDP-C 80-20 (Picolas) to get 250 µs pumping pulses, focused by a 3.18 mm diameter fused silica ball lens (67-384, Edmund Optics). The housing is designed to decrease heat flow from the cylinder head to the crystal by low thermal conductivity insets. The timing of the laser pulses was governed by a pulse generator triggered by an optical rotation sensor.

Fuels tested were hydrogen (99.99 mol %), methane (99.99 mol %), liquified petroleum gas (LPG) (C₃H₆–C₄H₈ 81–16 mol %; C₃H₆–C₄H₈ 30–64 mol %), butane (95 mol %), gasoline + castor oil, ethanol + nitromethane + castor oil (nitro fuel). Ignition possibility has been checked for equivalence ratios φ of 0.8 to 1.6. Since minimum ignition pulse energy (MPE) depends on this parameter significantly, engine operation was sensitive to this parameter too. We prepared gaseous fuel mixtures for direct injection into a gas bottle. Fuel gas filled the evacuated bottle through the leak valve (LV10K, Edwards) with pressure controlled by the membrane vacuum gauge (CTR 100, Ceravac), air was then supplied using a piston air compressor.

3. Results and discussion
We recorded the possibility of laser ignition and the minimum required laser pulse energy, as well as evaluated the engine operation stability and output performance with different fuel mixtures. Combustion completeness was controlled by CH and O₂ residuals in the exhaust (O₂ only for hydrogen); values similar to [9] were obtained. The engine being fed by a rich mixture φ ≈ 1.2 was able to spin up to 15,000 rpm without load. Since the engine started deceleration immediately after radiation switch off, glow or compression ignition did not take place. The Wankel engine has shown easier laser ignition with any fuel (especially liquid) than a two-stroke engine [6]. NOₓ emission for stoichiometric C₃H₆–C₄H₈ 81–16 mol % based mixture combustion was 6 ppm for the idling engine. Laser ignition leads to faster combustion core development than electric, so provides additional benefits for high-speed rotary piston engines. For maximum laser pulse energy of laser plug used (2.71 mJ) and compression threshold of 4 bar used to trigger laser pumping, successful ignition of H₂, CH₄, and LPG was observed in full φ = 0.8–1.6 range tested; for gasoline + castor oil, reach mixture limit was 1.2 and for nitro fuel—1.4.
The optical breakdown threshold was not so sensitive to the composition of the mixture; the value obtained was 1.5 mJ at $\phi = 1$, $p = 1$ bar. But breakdown does not necessarily lead to ignition. Data for comparison is available for $\text{H}_2$, $\text{CH}_4$, and $\text{C}_3\text{H}_8$ mostly at $\phi = 1$ and $p \approx 1$ bar. For $\text{C}_3\text{H}_8$, minimum ignition energy (MIE) is known to be 0.8 mJ [11], and that is the case when the significant difference comes from the methods of MIE and MPE measurement. The latter is a more correct parameter for laser ignition. At $\phi = 1$ and $p = 1$ bar, 82% of 2.5 mJ laser radiation was transmitted through the focal region; at lower energies still sufficient for breakdown, 98.5% was transmitted [12].

It is known that for electric ignition the meander of the MIE dependence shifts towards richer mixtures with an increase in the molecular weight of the fuel [13]. This is also confirmed for laser ignition at 1 bar: for $\text{H}_2$ MIE minimum was at $\phi \approx 0.85$ [14], for $\text{C}_3\text{H}_8$—at $\phi \approx 1.2$ [11, 15], and for $\text{C}_{12}\text{H}_{26}$—at $\phi \approx 3.7$ [11]. We have found that at pressure increase, meander of laser ignition MPE dependency on $\phi$ moves towards richer mixtures, but at the same time, it broadens making ignition less sensitive to pulse energy in a wider range of equivalence ratios. We actually could not ignite lean mixtures with our spark plug due to insufficient pulse energy. However, data confirming these features can be found in literature for other gases; nothing like this has been shown to date since very few works consider both different pressures and equivalence ratios.

Due to the narrow combustion chamber, it is difficult to ensure gas breakdown rather than ablation. We observed characteristic marks (not holes or grooves) on the piston surface. Ablation...
ignition is known to provide 10–30 times lower MPE values (for lean mixtures especially). That reduces pulse energy demand for the laser spark plug significantly. One would expect ablation at high repetition rate to lead to hole formation rapidly (at cca 10 nm/pulse rate), making such ignition mechanism impossible. However, we suggest that the piston material consumption is very low since oil and carbon films are constantly regenerated on top of it, so it is these that are ablated.

4. Conclusions
We have investigated laser ignition for the first time in a high-performance compact Wankel engine being fed with multiple fuels. We have also tested laser ignition of some fuels not reported before: nitro fuel and butane. It has been shown in principle, that such system operation is possible even without engine modification and within quite reasonable laser pulse energies, so, giving good perspectives for portable, UAV and electric transport applications. We have also shown that NO\textsubscript{x} emission can be significantly reduced for Wankel engines with laser ignition.

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