Exhaust composition at laser ignition of combustible gas mixtures under controlled conditions

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Abstract. One of the main advantages of laser ignition is the ability to ignite lean combustible mixtures, resulting in obvious economy and reduction of harmful emissions, primarily NO\textsubscript{x}. Experimental data on exhaust composition are presented in the literature very poorly. As a rule, the studies were not of a systematic nature, considered only very specific conditions of combustible mixtures exposure and composition (mainly methane-air), and were obtained for experimental piston engines, the design and operational features of which could significantly affect the result. We suggested that in order to obtain a starting point for further optimization, a study of exhaust composition should be carried out under conditions of minimal impact of the engine design. For this purpose, an experimental stand was created, which allows to investigate the laser ignition of combustible mixtures of different composition in wide pressures range. We studied the laser ignition of gas mixtures based on butane with fuel-air coefficients $\phi \sim 0.8 – 1.2$, in pressure range $p \sim 1 – 3$ bar, ignited by radiation of the the nanosecond Nd:YAG laser. The exhaust composition was analyzed by O\textsubscript{2}, CH, CO, CO\textsubscript{2}, NO\textsubscript{x}. Correspondence of the obtained results known from other experimental and theoretical works is analyzed.

1. Introduction
Laser spark is considered as one of the most perspective concepts of ignition for various types of engines for a number of reasons. With laser ignition, the engine efficiency may be improved and reliable operation at fuel lean mixtures can be achieved [1] making feasible savings in fuel consumption and reduction of harmful emission. The ignition process strongly affects combustion at its early stages in terms of flame quenching and extinction, exhaust composition, and energy efficiency. Every year emissions regulations become more and more strict for internal combustion engines, therefore, manufacturers conduct research in alternative ways of ignition [2]. Advantages of laser ignition in comparison with conventional spark plug were specified in [3]: ignition region can be located at optimum position inside the combustion chamber; no blanking effect of flame core by the spark plug electrodes; ignition of leaner mixtures (lower combustion temperatures, less NO\textsubscript{x} emissions [4,5]); no electrode erosion effects; increased engine efficiency due to higher ignition pressures possible; precise control of the ignition energy (also combined with electric discharge [6]); possibility of multipoint ignition [7, 8]; faster combustion.

The conducted laser ignition research have shown that fuel consumption and concentration of harmful gases is reduced. NO\textsubscript{x} emissions were found to be lower than at electric spark ignition [9–11]. Other works have shown that CO emissions were reduced by 18–25% at laser ignition and the CH emission by 14–17% [12].
There are several reasons for carbon monoxide formation: incomplete combustion of fuel rich mixtures due to lack of oxygen; presence of cold parietal layer in the traditional scheme of barrage at flame tube walls cooling; dissociation of CO$_2$ at high temperatures. The main ways of CO emission reduction are: ensuring the mixture composition in the combustion zone is closer to $\phi \sim 1.1–1.3$ ($\phi$ shows how actual fuel-air ratio is different to stoichiometric, it is greater than unity for fuel rich mixtures); increased combustion zone volume and the residence time. Reasons for nitric oxide NO$_x$ formation are high flame temperature and long residence time of combustion products in high temperature zones. Methods to reduce NO$_x$ emissions suggest using fuel lean mixtures ($\phi < 1$) and reducing residence time in the combustion zone. Generally, mutually opposite measures are necessary to reduce CO and NO$_x$ output. Laser ignition allows complete combustion of fuel, flame propagation speed increase, and burning temperature reduction. Thus leading to reduced NO$_x$ and CO emissions.

We have already tested exhaust composition at laser spark ignition of a gas fed two-stroke engine [13]. But certain engine construction strongly affects composition of the exhausts. So the aim of our present work was to obtain relevant data as close to combustion core as possible.

2. Experimental setup
Concentration of emission gases have been experimentally evaluated for butane based fuel from commercial gas burner cartridges (propane—6%, butane—28%, isobutane—60%, impurities—6%) in mixtures of different equivalence ratios ($\phi \sim 0.8–1.2$) at pressures ($p \sim 1–3$ bar). The fundamental frequency radiation (1064 nm) radiation of a nanosecond (12 ns) Nd:YAG laser (Solar LS LQ929) was focused by $F = 150$ mm double convex lens to induce a spark. Experimental setup (figure 1) was similar to that described in [14]. Combustible fuel-air mixture was prepared in evacuated combustion chamber by letting in fuel and then purging compressed air. After ignition, pressure in the chamber raised rapidly, when it reached 5 bar, the blow-off

![Experimental setup diagram](image-url)

**Figure 1.** Experimental setup: 1 – combustion chamber; 2 – Nd:YAG laser; 3 – blow-off valve; 4 – gas-analyzer; 5 – gas bottle; 6 – vacuum pump; 7 – valves; 8 – air compressor; 9 – volume for emission gases; 10 – pressure regulator; 11 – membrane vacuum gauge; 12 – acquisition unit; 13 – temperature controller; 14 – high pressure sensor; 15 – oscilloscope; 16 – energy meter; 17 – beam splitter; 18 – lens.
valve was automatically opened, and exhaust gases from the combustion chamber were drained to an elastic tank. Emission gases were accumulated in this volume after several shots, and then the gas concentration was measured using industrial gas analyzer (Autotest 02.03P, META).

3. Results and discussion

The results of emission gases analysis after laser ignition at 2 and 3 bar are presented at figure 2 for different mixture equivalence ratios. The nature of changes in curves is similar to the studies conducted for the electric-spark ignition [15].

$NO_x$ has a peak for nearly stoichiometric mixture, however, it becomes smoothened with pressure increase. For 2 bar, the peak of the $NO_x$ curve corresponds to $\phi \sim 0.9$, but shifts towards unity at 3 bar. $NO_x$ formation inside the combustion chamber strongly depends on peak temperature of fuel combustion behind the flame front, where nitrogen reacts with oxygen. The highest temperatures were obtained for mixture close to stoichiometric ratio, however, in this case there is no excess oxygen. So the peak shifts towards the lean mixture where temperature is still high, but an excess of oxygen exists. This results in high amount of $NO_x$. Similarly, $NO_x$ maximum is observed at intermediate value of $\phi \sim 0.9$ for electric spark ignition [16]. In this work $NO_x$ peak at laser ignition was shown even for lean mixture $\phi \sim 0.8$. In [17], $NO_x$ concentration was rising with pressure increase due to high combustion temperature. However, we got the

![Figure 2](image-url)
opposite results. To our mind, because at higher pressures gas stays in the combustion chamber for shorter time.

CO emissions are slightly lower for laser ignition compared to electric spark because of more efficient combustion at higher combustion chamber pressure. It is known that CO concentration increases significantly at mixture fuel enrichment. At laser ignition, this growth is less pronounced, and at higher pressures, it generally becomes insignificant. The nature of oxygen concentration change is opposite to CO. High concentration of O$_2$ occurs during lean mixture combustion. CO$_2$ emissions were slightly lower than at electric spark ignition.

Usual concentrations in electric spark ignited gasoline engines exhaust are: CO$_2$ (5–12%), NO$_x$ (100–8000 ppm), O$_2$ (0.3–8%), CH (0.2–3%), and CO (0.5–12%) for $\phi = 0.9$ [15]. Our results show that even at such low pressures of 2 and 3 bar, laser ignition ensures matching emission standards. So, significant emissions reduction is possible at higher pressures due to more complete combustion of fuel.

4. Conclusions

Even without catalytic exhaust systems and at lower pressure rates, laser spark ignition demonstrates the ability to reduce harmful emissions significantly. This provides the ability to match constantly increasing demands of harmful emissions regulation standards. Easier ignition of lean mixtures can also lead to fuel economy. Moreover, laser ignition system is less sensitive to fuel used, so very perspective for multi-fuel engines.

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