The gaseous hydrocarbon fuel combustion process diagnostics using laser-spark emission spectrometry

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Abstract. To solve the gaseous hydrocarbon fuel combustion process control and diagnostics problem, it is proposed to apply the laser-spark emission spectrometry methods. In propane-air mixture combustion, three modes are investigated: stoichiometric combustion, an enriched mixture, and a lean mixture. A laboratory stand has been developed to study combustion processes by laser-spark emission spectrometry. The plasma radiation spectral characteristics an experimental study results formed in a flame when exposed to laser radiation are presented.

1. Introduction

In the world, electrical energy most is produced using the burning fossil fuel chemical energy, which is mainly used as organic substances extracted from the earth bowels in their artificial processing hydrocarbons or products form [1]. At the same time, the fuel combustion control and optimization issues in thermal power plants are especially relevant to increase its use efficiency and protect the environment.

The existing system's majority operation principle for monitoring and diagnosing combustion processes is based on measuring indirect parameters: temperature, pressure and vacuum in furnace various parts, the gas and airflow rate supplied to the furnace, the flame colour image, the combustion products components concentration, etc. [2-4]. Measurements by indirect signs significantly impair the control information content and reliability of performed by, reduces its performance.

Improving the control quality and combustion processes optimization at heat and power facilities can be achieved through the control of new methods and technical means development and implementation, which make it possible to meet the constantly increasing requirements for the aforementioned facilities power and dynamic performance. Since the optical radiation emitted as the combustion process a result has a certain spectral composition [5], the applied optical spectrometry methods use for solving the monitoring combustion processes problem seems to be the most promising.

Attempts to use optical spectrometry in traditional methods to control combustion processes have been going on for a long time [6, 7]. In this work, to solve the combustion processes monitoring and diagnostics problem, it is proposed to use one of the most modern laser analytical methods - laser-spark emission spectrometry [8].

2. Laser-spark emission spectrometry method in combustion processes diagnostics

The laser spark emission spectrometry method (LIBS-spectrometry) is based on measuring the secondary radiation spectra generated during the plasma formation and evolution when a substance is...
exposed to powerful laser radiation. To obtain a spark on the materials surface under study, solid-state lasers with a high Q factor and a short pulse duration are usually used, which makes it possible to avoid significant heat transfer throughout the sample volume (only local heating in the laser beam focusing region and laser radiation screening by the plasma formed at the laser pulse end [8]).

The LIBS method has advantages in a number over traditional spectral emission methods [8]: high sensitivity; the ability to analyse the sample's elemental composition in aggregation in various states: solid, liquid, gaseous; the exposure zone small size to laser radiation allows for the elemental composition local control; no preliminary sample preparation is required; remote analysis possibility.

The hydrocarbon fuel combustion process is based on the combustible fuel components chemical interaction with an oxidizer, which is mainly used as atmospheric air. And combustion efficiency is determined by the air-fuel ratio. In this case, the combustible mixture composition can be characterized by the parameter $\alpha$. If $\alpha=1$, the mixture is stoichiometric, i.e., this is the mixture composition in which the oxidant amount corresponds to that required for the hydrocarbon complete combustion; $\alpha=0.5$, the mixture is called rich, i.e., with half (compared to stoichiometric) oxidant content; $\alpha=2$ - lean mixture with doubled oxidant content [1]. An optimal balance between fuel and air is key to maximizing combustion efficiency and reducing harmful emissions.

The combustion process is a complex dynamic process with a constantly variable composition, and this process control requires more accurate and sophisticated methods and technical means.

The laser-spark emission spectrometry methods make it possible, in real-time, during combustion, not only to control the air-fuel ratio but also to perform substances a qualitative and quantitative analysis involved in the combustion process. For example, in [9], the air-fuel ratio during methane-air mixture combustion was calculated on the hydrogen H measuring the radiation intensities basis (656.3 nm) and oxygen O (777 nm) and determining their ratio. It has been shown that the air-fuel ratio increases linearly with an increase in the hydrogen intensity ratio to oxygen H/O. It was shown in [10] that the ratio of the intensities H (656.3 nm) to O (777 nm) and C (833.5 nm) to O (844.6 nm) obtained from a Bunsen burner laminar flame has a strong correlation with the air-fuel ratio. Spectroscopic lines were determined for N (746.3 and 743.8 nm), and CN (broad emission 707-734 nm).

This paper presents the gaseous hydrocarbon fuel combustion process, an experimental study results by the LIBS spectrometry method. Propane was chosen as the hydrocarbon fuel due to its availability for laboratory research.

3. Propane combustion diagnostics experimental studies by libs spectrometry methods

The experimental setup is shown in figure 1.

The experimental setup consists of Nd:YAG laser, which is a LOTIS II 2134U solid-state laser with a lasing wavelength of 1064 nm; Beam expander Eksma Optics 160-0051; a focusing lens, which is an ACA254-150-1064 air gap doublet with a focal length of 150 mm; two-component burner, which provides for preliminary mixing of gas and air supplied by the compressor; gas cylinder propane C3H8; an optical telescope to which an optical fibre is attached; a two-channel spectrometer, which is used as AvaSpec-ULS4096CL-2-EVO. The spectrometer first channel has an operating range of 240 nm - 510 nm, the second - 490 nm - 1030 nm; the PC is a personal computer.

The propane-air mixture burned at atmospheric pressure. A LOTIS II 2134U laser radiation with 1 Hz frequency, previously passed through a beam expander with a 5x magnification, is focused on the flame by an ACA254-150-1064 doublet. The pulse energy during the experiment was 25 MJ, which, taking into account the optical scheme, is sufficient for flame breakdown and plasma formation. Plasma radiation is captured by an optical telescope connected to an optical fibre. In this case, the laser radiation optical axis incident on the flame and the plasma spectrum capture system axis were at an angle of 45 degrees.

Plasma radiation through an optical fibre enters the AvaSpec-ULS4096CL-2-EVO spectrometer corresponding channel, which transmits the obtained spectroscopic information for display on a PC.
Figure 1. The experimental setup diagram.

The experimental setup a photograph is shown in figure 2, 1 - LOTIS II 2134U Nd:YAG laser, 2 - Eksma Optics 160-0051 beam expander, 3 - ACA254-150-1064 doublet with holder, 4 - Teklu-type torch, 5 - cylinder cable with C3H8 gas, 6 - optical telescope, 7 - optical fibre, 8 - AvaSpec-ULS4096CL-2-EVO spectrometer, 9 - PC.

Figure 2. The experimental setup photo.

The experiment was carried out at three different gas/air ratios: $\alpha \approx 1$ (the mixture is close to stoichiometric); $\alpha = 0.75$ (rich mixture); and $\alpha = 1.25$ (lean mixture).

Figures 3–5 show the plasma radiation spectral characteristics formed in the flame at different gas/air ratios. The presented spectral characteristics are summarized from two spectrometer channels: 240 nm - 510 nm and 490 nm - 1030 nm.
Analyzing the experiments’ results, the following conclusions can be drawn:

- The plasma emission spectrum generated in the propane flame exhibits a peculiar stripe structure in the specific spectral bands a number form corresponding to the combustion products: hydrogen H, oxygen O, nitrogen N and carbon C.
- The most intense lines correspond to the hydrogen H spectral lines (656.3 nm) and oxygen O (777 nm). The hydrogen H less intense lines (486.1 nm), oxygen O (844.6 nm), nitrogen (doublet: 743.8 and 745.4 nm, 821.6 nm and 868.3 nm), carbon (245 nm, 908.9 nm and 940.6 nm) and the molecular CN bands (350-420 nm) are also observed.
Figure 5. Plasma radiation spectral characteristic formed in the flame at $\alpha=1.25$ (lean mixture).

There is the spectral lines’ ratio a linear dependence corresponding to the H (656.3 nm)/O (777 nm) peaks on the gas/air ratio. The H/O intensity ratio increases linearly with increasing gas/air ratio.

4. Conclusion
In this paper, laser spark emission spectrometry methods have been proposed to solve the gaseous hydrocarbon fuels monitoring and diagnosing the combustion process problem.

As the research part, an experimental stand was developed using a two-component burner, which provides for gas and air preliminary mixing supplied by a compressor.

An experiment to study the plasma radiation spectral characteristics formed in a propane flame was carried out for three cases: a mixture close to stoichiometric, enriched and depleted mixtures. It was found that the most intense lines correspond to the hydrogen H and oxygen O spectral lines; nitrogen and carbonless intense lines were also observed. The H/O spectral line ratio dependence on the gas/air ratio was also established. The H/O intensity ratio increases linearly with increasing gas/air ratio.

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