Narrow-band optical filter for a spectral-selective control device of physical and physicochemical processes

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Abstract. Subject of the present paper is the application of a multichannel optical spectrometer performing spectral measurements in specified areas of the optical range using a set of narrow-band interference optical filters that are tuned to certain wavelengths. Tasks of monitoring and controlling the physical and physico-chemical processes and the prospects of using non-contact optical spectroscopy for their solution are considered. Recommendations are given both on the choice of materials for infrared and visible filters. A visible range filter based on a combination of zirconium oxide and silicon oxide layers has been developed.

1. Introduction
One of the actual problems in ecology is the study of the relationship between man and nature. In most cases, industrial enterprises in the production cycle involved physical and physico-chemical processes that are accompanied by emission of electromagnetic radiation in the optical range. First of all, such processes include combustion processes, for example, in internal combustion engines, gas turbine and rocket engines, in various furnaces, boilers, heat power plants and units, as well as smelting processes in metallurgy. Monitoring and control of combustion processes is a necessary condition for safety at such enterprises and leads to a significant reduction in fuel costs and a reduction in emissions of undesirable combustible and greenhouse gases into the atmosphere.

The most informative control methods are spectroscopic methods. As a result of the analysis of emission radiation spectrum, it is possible to obtain extremely diverse information about the ongoing process or condition of the object, as well as to highlight a number of informational signs, on the basis of which it is possible to carry out a control procedure for these processes. Of particular relevance are the methods of optical spectroscopy in the analysis of various processes occurring under extreme conditions (high temperature and humidity, aggressive chemical environment, etc.).

The present paper proposes the construction of a spectral-selective control device in the form of a multichannel optical spectrometer of non-contact analysis [1]. Contactless analysis refers to such type of spectroscopic measurements, where direct contact of the device resolving system with the radiation field is excluded by the use of a -optical fiber, and thereby eliminates the negative environmental impact on the device and the measurement results.

2. Monitoring and control of combustion processes by optical spectrometry methods
One of the objective sources of information on combustion processes is the spectral composition of electromagnetic radiation emitted by a flame. Certain spectral bands and atomic lines are of interest...
for specific applied problems. Such tasks include the study of combustion processes in the furnaces of heat power plants [3], internal combustion engines, gas turbine [4] and rocket engines [5,6], the tasks of monitoring and controlling various technological processes in the metallurgy, for instance, control of the steel smelting or vacuum arc remelting processes [7], etc.

The actual problem in the development, testing and operation of gas turbine engines is to control the composition of the combustion products and ensure stability in all modes of their operation. In addition, pollutant emissions from aircraft near airports and at altitude are of great public concern for their impact on the environment and human health [4]. The main pollutants emitted by aircraft are exhaust gases (NO\textsubscript{x}, H\textsubscript{2}O, CO, CO\textsubscript{2}, and SO\textsubscript{2}) and aerosol particles (mainly smoke/soot). Optical spectrometry methods allow high-resolution and real time monitoring of the flame spectral distribution in the combustion chamber and the intensity of its radiation, including in certain areas of the optical spectrum where the own radiation of the above chemical compounds takes place.

In the practice of aerospace engineering, the problem of diagnostics liquid rocket engines during ground testing to prevent various malfunctions in engine components. Such malfunctions can lead to destruction of the engine and test complex. For this diagnostics the atomic emissions for 10 elements comprising the alloys of the liquid rocket engine are monitored and their contributions in the plume are quantified. These 10 elements are: Ni, Fe, Cr, Co, Mn, Cu, Ag, Al, Ca, and Pd [5]. The primary atomic emission lines with most intense of these elements occur in in the short-wave range of the spectrum of 320-500 nm. It is enough to analyze certain regions of the engine plume radiation spectrum in which these atomic lines of metals lie for carrying out this diagnostics. A spectral resolution of 1 nm is sufficient in order to identify the chemical element from the spectrum [6].

Another task of the combustion processes control is the monitoring, control and optimization of combustion in various fired heaters, boilers and heat power plants to increase the efficiency and safety of their work, as well as limiting the negative impact on the environment. The solution to this problem is seen in the application of optical spectroscopy methods to control the process of burning fuel in a boiler furnace. It is possible to control not only the composition of the burned fuel and its quality, but also its consumption by analyzing the obtained spectroscopic information. Thereby it allows not only increasing the efficiency of the control procedure, but also replacing a huge number of sensors and equipment with one spectral device.

Metallurgy is another promising area application of combustion control systems based on optical spectrometry. The steel composition is controlled by taking a sample and its spectral analysis carried out by the traditional method in a special factory laboratory. It requires considerable time and does not allow real-time control of the steel smelting process. Using of optical spectroscopy methods is also possible in vacuum-arc melting.

The above combustion processes occurring under extreme conditions: high temperature and humidity, aggressive chemical environment, etc. In addition, it is sufficient to analyze specific spectral lines or certain spectral bands to successful solve these tasks. A spectral-selective control device in the form of a multichannel noncontact optical spectrometer can be successfully used to solve these tasks. Fiber-optic transmission system will provide opportunities to place the device at a given distance from controlled objects. This will allow not only to eliminate the negative environmental impact on the device and the measurement results, but also to carry out measurements in real time in the all of interest areas of spectrum.

3. Control device in the form of a multichannel optical spectrometer

Using a spectral-selective control device in the form of a multichannel optical spectrometer is proposed to solve the problem of control physical and physico-chemical processes in this paper. The novelty of the device is a fiber optical bundle and N parallel channels of spectrum analysis using [1]. Each channel contains a narrow-band optical filter. The block diagram of a multichannel optical spectrometer is shown in figure 1, where OC is object of control (combustion process); FO is forming optics; FOB is fiber optical bundle; L1 is the first collimating lens; OF is narrow-band optical filter; L2 is the second collimating lens; Ph is photodetectors; PU is processing unit; PC is the computer.
Figure 1. Block diagram of a multichannel optical spectrometer.

The spectral decomposition of optical signals is performed by a set of narrow-band interference optical filters in this device. Applying of a fiber optical bundle allows to transfer the device to a safe distance from the combustion source for it. Resolution of spectrometer is determined by the passband of a narrow-band optical filter due to the features of the principle of its operation. In this connection distortion of an optical radiation wave front that occurs when it passing through an optical fiber does not affect the parameters of the device and the results of measurement [2]. Spectroscopic information about the controlled combustion process is displayed on the computer.

The success of creating such instruments for control combustion processes is directly related to the improvement of the technology that allows implementing band-pass interference optical filters with a sufficiently narrow bandwidth and in a wide analyzed wavelengths range.

4. Bases of interference filter development. Methodology assessment of synthesis quality of and manufacturing

The manufacturing and synthesis of optical coatings for reflection or transmission of optical radiation in a given wavelength range is based on interference from multiple layers of the film structure. Each layer of this structure has a thickness \( d_k = \frac{0.25 \lambda_0}{n_k} \), where \( \lambda_0 \) is the center wavelength, which corresponds to either the minimum or maximum transparency, \( n_k \) is the refractive index of the \( k \)-th layer of the film. Materials such as magnesium fluoride (MgF\(_2\)), calcium fluoride (CaF\(_2\)), barium fluoride (BaF\(_2\)), quartz glass, zinc sulfide (ZnS), cadmium telluride (CdTe), silicon (Si) and germanium (Ge) should be used to implement optical band-pass or band-block filters in the infrared range, and for the visible range – silicon oxide(SiO\(_2\)), quartz and borosilicate glasses, zirconium oxide (ZrO\(_2\)) [8]. The synthesized filter in the visible range is shown in figure 2. Its optical structure based on a layer system can be written as \( A_0(xHlxH)\hat{q}S \), where \( A_0 \) is the air medium; \( S \) denotes the substrate; \( H \) designates the layer with a high refractive index and a thickness with a wavelength of \( \lambda_0 \approx 570 \text{ nm} \), corresponding to the middle of the blocked interval with a width of \( \Delta \lambda = 60 \text{ nm} \) \( (\lambda_{\text{min}} = 540 \text{ nm}, \lambda_{\text{max}} = 600 \text{ nm}) \); \( L \) is a layer with a low refractive index and thickness; the numerical factor \( x = 0.5 \) in front of the layer symbol \( H \) means that the layer thickness is adjusted in the synthesis process in proportion to \( x \); the degree \( ^{\hat{q}} \) denotes the number of times that the system is written in brackets and is related to the number of layers by the relation \( N = 2q + 1 \). This band-stop filter was synthesized from layers of zirconium oxide with a refractive index of \( n_H \approx 2.1 \) and silicon oxide with \( n_L = 1.46 \) at \( q = 80 \) on a K-8 grade borosilicate glass substrate. It is known that the larger the curve corresponds to a rectangular shape to the larger the \( q \) value. In this case, strong oscillations are most often observed outside the \( \Delta \lambda \) interval.
5. Conclusions
This paper proposes the principle of constructing a spectral-selective device for physical and physico-chemical processes control in the form of a multichannel optical spectrometer. This device carries out a non-contact analysis of the spectrum of the combustion source using a set of narrow-band interference optical filters that are tuned to certain wavelengths and provides spectroscopic information in predetermined specified areas of the analyzed flame emission spectrum. The success of creating such instruments for control physical and physico-chemical processes is directly related to the improvement of the technology that allows implementing band-pass interference optical filters with a sufficiently narrow bandwidth and in a wide analyzed wavelengths range.

A visible range filter based on a combination of zirconium oxide and silicon oxide layers has been developed. It is shown that in the working wavelength band an effective approximation to the desired shape of the transmission spectrum is achieved only with a very large number of layers.

A detailed description of the developed laboratory set-up and its experimental study was presented in [9]. An experimental study was carried out to determine the spectral line of copper Cu when burning copper powder the spectral line of Na when burning sodium chloride (NaCl). The obtained research results are encouraging and prove the efficiency of the developed device.

Acknowledgment
The work was supported by the Russian Science Foundation (RSF, Grant № 19-79-10110).

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