Monitoring systems of the combustion processes based on optical spectral devices

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Abstract. The article considers the application of optical spectroscopy methods to address the problems of physical and technological process control. Such processes often run under extreme conditions. Therefore, to eliminate the negative influence of these conditions on a spectral device, it is proposed to use an optical fibre transmission system. It is shown that these devices can be described as multidimensional systems, the characteristics of which are given in matrix form. This enables forming up to N informative parameters characterising the course of the process.

1. Introduction

The course of physical and technological processes, accompanied by the optical radiation emission, is characterised by several informative parameters, including spectroscopic ones. Studying the spectral composition of optical radiation from a controlled process or object provides plenty of information, the dynamical data included.

This article proposes a new approach based on non-contact optical spectroscopy methods to solve the problem of multi-parameter control of physical and technological processes. Non-contact spectroscopy is understood as such a spectroscopic measurement which excludes any direct contact of the device resolving system with the source radiation field. This can be realised by using an optical fibre transmission system (OFTS). The obtained spectroscopic information enables to carry out the multi-parameter control procedure, where a conclusion about the state of the controlled process is based on the comparison and analysis of several informative parameters in the optical spectrum.

2. Application of spectroscopic methods in control problems

Currently, there is a tendency to impose more tough requirements for energy efficiency and reduce the ecological burden during the operation of technical objects of heat-power engineering and various transport systems. For example, in gas turbine engines [1, 2], in addition to monitoring the combustion efficiency, the composition control of combustion products is applied, which enables increasing the stability and efficiency of the engines' operation while reducing the hazardous substance emissions. The study of fuel combustion and hazardous substance formation by spectroscopic methods enables predicting the most important characteristics of an installation. What is more, it allows estimating the hazardous substance emissions (NOx, CO, CO2, SOx, HNO2, HNO3, H2SO4, organic substances, CnHm) and aerosol components (soot particles, aerosols). That is why the authors consider the method of optical spectroscopy as ideal for solving this problem since the study of the flame plume spectral distribution...
and the identification of the above chemical substances in it provides objective information about the engine operation.

Another problem, for the solution of which the method of contactless spectroscopy can be applied, is the control and optimisation of combustion in boiler furnaces. This will improve the energy complex efficiency and reduce the ecological burden on the environment. Existing solutions to optimise the combustion process in furnaces consist in measuring the parameters: temperature, vacuum and gas pressure, supply air pressure, concentration of combustion product components (CO₂ and O₂) and incomplete combustion products (CO, H₂ and CH₄), measurement of fuel consumption rate to determine the fuel-air ratio [3-5], etc. Such a control system requires many different types of sensors, which slows down the operation and reduces the control process effectiveness. Spectroscopic combustion control systems can replace the existing ones. The received spectroscopic information helps to control both the composition of the combusted fuel and its quality, as well as to control the hazardous substance emissions into the atmosphere.

An urgent problem in the aerospace industry is diagnosing emergency conditions of liquid-propellant rocket engines during their bench tests [6-8]. Such a diagnostics is a mandatory step to prevent various malfunctions in engine components and assemblies, which can lead to malfunctioning or complete engine failure, as well as to an emergency. This diagnostics is based on monitoring the appearance in the engine flame, and dynamics of the spectral lines glow characteristic of such structural materials as Al, Fe, Cu, Cr, C, Cu, Co, Ni, Ti, W, Mg, etc. The lines of a specific chemical characterise the wear or destruction of a specific unit (bearings, turbine blades, combustion chamber, etc.).

The problems of controlling technological processes in metallurgy include vacuum-arc remelting, which is a melting and solidification process used for the production of high-quality metal ingots (steel, titanium, molybdenum, tungsten, etc.) [9, 10]. In this technological process, emergencies may occur when copper molds are burned through during melting. It occurs when the arc passes from the liquid metal bath to the wall of the water-cooled copper shell of the mold. The burn-through process takes a few seconds and is followed by the optical radiation emission at the wavelengths corresponding to the copper spectral lines. Detecting this radiation by spectroscopic methods enables the control of this technological process.

Optical emissions from the above objects of control are characterised by line spectra, most commonly, by a certain set of spectral lines, which means that to control such objects there is no need to have information about the entire continuous spectrum of radiation. It is enough to have a set of reference values of the spectrum on predetermined wavelengths. In addition, the multi-parameter control implies that spectroscopic information must be presented in a discrete form. These circumstances impose the corresponding requirements for spectral devices, which are supposed to be used in multi-parameter control systems. First of all, this is evident as the fact that spectroscopic information should be provided to the operator in the form of reference values, i.e. in the matrix form. Thus, the most suitable spectral devices for multi-parameter control are a multichannel optical spectrometer and a spectral device with a diffraction grating able to read spectroscopic information using a CCD ruler.

3. Control systems based on optical spectral devices

3.1. Spectral device with diffraction grating
Figure 1 shows a block diagram of a spectral device with a diffraction grating, which is a measuring device in the control system.

The device includes sequentially located OFTS, a shaping optics system, a diffraction grating, an optical coherent Fourier transform processor with a CCD ruler located in the rear focal plane of the lens.

The OFTS includes an optical system designed for efficient input of the analysed radiation into the fibre, an optical cable, and an output system. When radiation is transmitted through the OFTS, the front of the wave emerging from the radiation output system is different from the required homogeneous and flat one, which is corrected by the shaping optics system, and then the radiation is fed to the diffraction grating. The use of OFTS enables remote study of processes occurring in extreme conditions (for
example, high temperature, aggressive chemical environment, etc.). In this case, the extreme conditions only affect the system for radiation input into the fibre, and the device can be removed at a considerable distance from the object.

The spectrometric information is read out using a multi-element photodetector – a CCD ruler. This feature of reading determines the simultaneous formation of up to \( N \) informative parameters reflecting the course and state of the controlled process.

A detailed description of obtaining reference photocurrent values from each pixel of the CCD ruler is given in [11]. Thus, the spectrum reference values are the set of photocurrents of all elements of the CCD ruler, that can be represented in matrix form:

\[
\begin{bmatrix}
i_1(\omega_1) \\
i_2(\omega_2) \\
\vdots \\
i_N(\omega_N)
\end{bmatrix} = \int_{-\infty}^{\infty} \begin{bmatrix} B_1 \cdot A_1(\omega,\omega') & 0 & \cdots & 0 \\ 0 & B_2 \cdot A_2(\omega,\omega') & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & B_N \cdot A_N(\omega,\omega') \end{bmatrix} G(\omega') \\ \text{d}\omega' \quad .
\]

where \( G(\omega') \) – energy spectrum of the analysed signal from the controlled process/object; \( \text{diag} \{ \ldots \} \) – energy instrument function of the device with a diffraction grating in matrix form; \( A_i(\omega,\omega') = \text{sinc}^2(\cdot) \).

3.2. **Multichannel optical spectrometer**

Figure 2 shows a block diagram of a multichannel optical spectrometer [12]: CO – control object; SO – shaping optics; FOB – fibre optic bundle; OFU – optical filtering unit; Ph – photodetectors.
The resolving system of a multichannel spectrometer consists of a set of narrow-band optical filters. In the case of using this spectrometer in a process control system, the central wavelengths of the filters are selected to correspond to those spectral lines that are specific for the controlled process, and their number is determined by the required number of analysed lines or spectral sections. The fibre optic bundle enables introducing radiation into the filtering units, as well as to take away the spectrometer at a safe distance from the controlled process. This is of great importance when the spectrometer under consideration is used as a multichannel measuring device in a control system operating under extreme conditions.

Spectrometric information in a multichannel spectrometer is read by the photodetectors installed in each channel. Therefore, the readings, which are the reference values of the spectrum averaged over the frequency band of each filter, can also be represented in matrix form.

A theoretical analysis of the spectral processing of a signal with such a spectrometer was given in [12], according to which the averaged values of the photocurrent obtained from each channel of the device can be represented in the following form:

\[
\begin{bmatrix}
  i_1(\omega') \\
i_2(\omega') \\
\vdots \\
i_n(\omega') \\
\end{bmatrix} = \frac{1}{T} \int_{-\Delta\omega}^{\Delta\omega} \begin{bmatrix}
  M_1 \cdot W_{11}(\omega, \omega') & 0 & \ldots & 0 \\
  M_1 \cdot W_{12}(\omega, \omega') & M_2 \cdot W_{22}(\omega, \omega') & \ldots & 0 \\
  \vdots & \vdots & \ddots & \vdots \\
  M_1 \cdot W_{n1}(\omega, \omega') & M_2 \cdot W_{n2}(\omega, \omega') & \ldots & M_n \cdot W_{nn}(\omega, \omega') \\
\end{bmatrix} \begin{bmatrix}
  G(\omega') \\
  G(\omega') \\
  \vdots \\
  G(\omega') \\
\end{bmatrix} d\omega'.
\]  

where \( W_{nm}(\omega_n, \omega') \) – energy instrument function of the \( n \)-th spectrometer channel,

\[
W = \int_{-\Delta\omega}^{\Delta\omega} \frac{\sin^2[(\omega-\omega')T/2]}{[(\omega-\omega')T/2]^2} d\omega'.
\]

The given values of the monitored conditions are set in the form of voltages proportional to the average currents.

4. Conclusion

This work proposes to use a multichannel spectrometer and a diffraction spectral device as measuring devices in control systems for physical and technological processes. These devices can be described as multidimensional linear systems that provide spectrometric information in matrix form as a set of state variables of the controlled process.

Thus, it is feasible to create automatic control systems based on optical spectroscopy methods, which function around a variety of controlled parameters formed by measuring a variety of intensity values of different parts of the spectrum, including individual spectral lines. Therefore, these parameters can form hierarchical levels.

The use of optical spectroscopy methods enables the creation of qualitatively new automatic control systems, including the systems minimising the environment-damaging substance emissions, which are the result of these processes.

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