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Mathematical modeling and control the process of fuel combustion in gas combustion furnaces

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Abstract. In this manuscript, the results of mathematical modeling and control of the fuel combustion process in gas-burning furnaces are presented. The physical principles of constructing a primary measuring transducer for the selective measurement of the concentration of harmful substances (CO) and (C_nH_m) in exhaust gas mixtures are substantiated based on the spectrophotometric method of measurement in the absorption bands of the IR range, which ensures selectivity in determining the target parameters. An original combined optical scheme of a three-component (hydrocarbons, carbon monoxide, and dioxide) gas analyzer based on the infrared measurement method has been developed. A meaningful statement is made and a solution is given to the problems of automatic control of the efficiency of the fuel combustion process as an extremal problem of maximum speed. The efficiency of the system functioning is characterized by the amount of losses caused by the search for the optimum of the statistical characteristics of the dynamic object under study. A comparative analysis of methods for solving problems of extreme control by "increment" and by "second difference" indicates that the performance and quality of regulation is not inferior to the well-known traditional systems for controlling the efficiency of fuel combustion in gas-burning furnaces.

1 Introduction

Recently, special attention in the world has been paid to the tasks of automatic control and management of complex technological processes of fuel combustion in gas furnaces and automatic control systems for thermal processes, as well as transferring the results in the form of advice to the operator or downloading to a computer in the form of signals - control actions on actuators, located at the control facilities. The use of the means of the fourth industrial revolution, called “Industry 4.0” [1, 2], for the purpose of ensuring energy and resource saving in heat-technological processes of the chemical, petrochemical, metallurgical, food industries and in the production of building materials occupies a leading position. In this regard, in the developed countries of America, Europe, and Asia, a global map of the degree of use of the means of the fourth industrial revolution in the industry, in which a special task is the implementation of an extremely automated control system that provides multi-parameter control and support for energy-saving technologies has been developed.

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It has been shown that automated control of gas-burning installations increases the reliability and technical and economic indicators of technological installations and furnaces [3-6]. At the same time, fuel losses are largely associated with the improvement of the combustion of the latter.

When implementing extreme regulation, the optimal parameters of the fuel combustion process are determined by analytical or experimental methods based on the results of a study on operating gas-burning furnaces. Open-loop systems of extreme regulation can have a significant static error. At the same time, the search for the extremum of the static characteristic of the object is performed using search techniques, during which the sign and absolute value of the deviation of the operating point from the optimum are revealed and movement is carried out in the direction of the extremum. This class of high-speed linear systems directly controls the current value of the optimum [4, 7], which characterizes the quality of the control system functioning.

Reliable and trouble-free operation of gas-burning plants largely depends on solving the problem of the functioning of heat-stressed heating surfaces in the form of furnace screens, characterized by a significant number of structural and operational parameters that reflect the aerodynamic mode of operation of gas-burning furnaces and their design. The structure and geometry of the flame in the furnace chamber predetermine the temperature profile and the gas composition of the heat flow throughout the entire space of the gas combustion plant. The currently used methods for measuring thermal loads, inserts, portable thermal probes, and others do not meet the requirements. The above conclusions indicate the need to develop algorithms for monitoring and controlling the combustion process in gas-burning furnaces and their practical application in solving automation and process control problems.

2 Formulation of the problem

The design of the measuring transducer is based on the method of spectrophotometric gas analysis [8, 9], the advantage of which is the relative simplicity of the constructive implementation of the measurement method, speed, the possibility of performing single- and multi-component measurement analysis, as well as the high selectivity of the analysis of carbon oxides (CO) (has absorption band I_{max} = 4.7 μm); methane (CH_4), propane C_3H_8 and other types of hydrocarbons (3.4 μm), carbon dioxide (CO_2) (has an absorption band of 4.27 μm).

It has been established that under real conditions the dependence of the transmittance on the concentration of the gas mixture deviates from the exponential form of the Beer-Bouguer law:

$$U = U_0 \exp(-acl)\,, \tag{1}$$

where a – gas mixture flow absorption coefficient; U_0 – incident beam intensity; c – gas mixture concentration; l – beam path length.

In [10, 11], it is theoretically substantiated that the measurement error is achieved at a metric density value of 0.4. Following dependencies has been received:

$$dc/c = Sc*c = -0{,}4353dT/(T\lg T) = 0{,}4343S_T/(T/\lg T)\,, \tag{2}$$

or

$$\Delta c/c = 0{,}4343\Delta T/T\lg T\,. \tag{3}$$

As a result of the corresponding transformations, the following dependence was obtained:

$$Sc/c = S_A/A = 0{,}4343 S_T/10 - A \cdot A_c\,, \qquad (4)$$

in which the parameter is detected on the basis of 5÷10 parallel readings; $A = a \cdot l \cdot c$; $T = 10 - A$.

Following theoretical and experimental methods established:

– expressions (2) and (4) have an underestimated reproducibility and it is possible to carry out the photometry process with much higher reproducibility with a concentration error Δ of less than 0.88%, resulting from expressions (2) and (4);

– for the interval of single-beam spectrophotometers and double-beam photocolorimeters, optical densities, in which the total measurement error does not exceed twice the minimum error, in contrast to the generally accepted value (0.12-1.2), reaches values in the range (1.35 - 1.45);

– the measurement area at $A \le 0{,}1$ is unfavorable due to the sharply increasing values of the error Δ. It has been established that in each specific variant, in order to ensure the best reproducibility, it is advisable to identify the optimal measurement area, taking into account the instability and sensitivity of the gas analyzer. The acceptable range of optical densities is from 0.1 to 0.7. The undesirability of performing measurements at optical densities above 0.7 is due to the low level of the measured parameter.

Another factor that is of significant importance when choosing the length of the cuvette is its physical volume. In this case, the criterion of the length of the optical path of the cuvette is more acceptable. We chose it equal to 145 mm, since for a given optical path length, the parameters of the gas layers under consideration at the maximum amounts of CO (10% vol) and C_nH_m (1% vol) take place, the following: their optical densities are quite close D_{CH} (1 vol) = 0 .48 and D_{co} (10% vol) = 0.84.

In this work, a study was made of a gas analyzer designed to control the concentrations of carbon monoxide, hydrocarbons, and carbon dioxide (CO) in gas emissions. Since all three analyzed components are active in the infrared (IR) region of the spectrum, a high selectivity of measurements is appropriate. The non-dispersive infrared method was chosen as the analysis method.

The maxima of the absorption bands of these gases are at wavelengths L_1 = 3.39 μm (for hydrocarbons), L_2 = 4.26 μm (for carbon dioxide), L_3 = 4.6 μm (for carbon monoxide). The absorption bands do not overlap with each other or with the absorption bands of interfering components. In addition, there is a spectral range (3.8 - 4 μm), in which there is no absorption of radiation by any of the gases present in the analyzed mixture, and, therefore, the wavelength L4 = 3.9 μm can serve as a reference. To achieve high metrological parameters, IR gas analyzers are used, built according to a single-beam multichannel scheme. In this case, the channel is understood as the spectral region in which the measurement of the gas transmission value is carried out. For the analysis of the above three components of the studied gas mixture, four channels are required: three working and one reference. It has been established that in order to obtain the optimal optical density of the gas, the lengths of working cuvettes for dioxide are 0.4 cm, for hydrocarbons and carbon monoxide are 14.5 cm. Proceeding from this, an original combined optical scheme of a gas analyzer is proposed, consisting of two identical radiation sources 1 and 1' (Fig. 1) representing lamps TRS 1500-2300; lenses 2 and 2' for the formation of light fluxes of radiation; beam-splitting plate 3, with which two light fluxes are mixed; two working cells 4 and 5, through which the analyzed gas mixture is sequentially pumped (the length of the working cell 4 is 14.5 cm, cells 5 is 0.4 cm); disk 6, on which four interference filters 7 are installed; a motor 8 driving the disc 6 in rotation; lenses 9; photodetector 10, which is a cooled temperature-controlled photoresistor FUO-614.

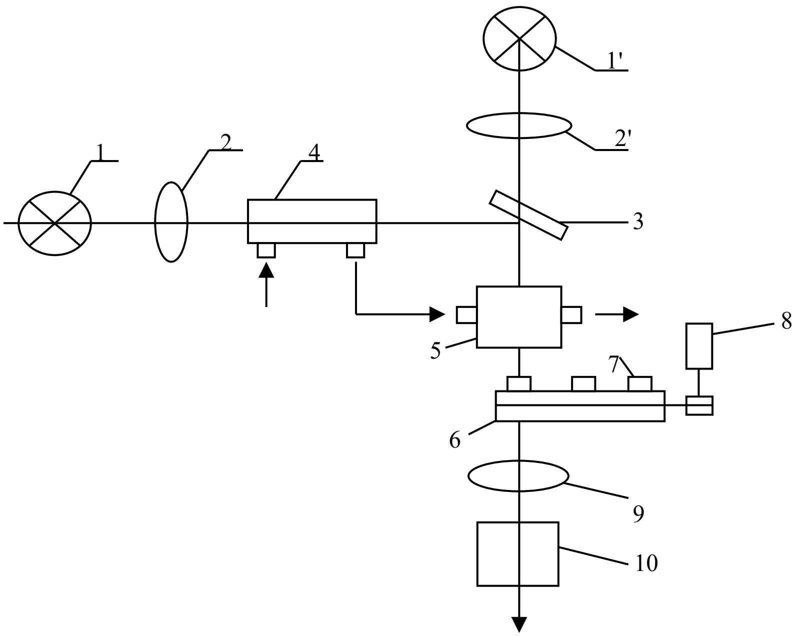

Fig.1. Optical scheme of the gas analyzer.

The radiation from the lamp 1 passes through the cuvette 4, is reflected from the beam splitter 3, enters the cuvette 5 and then to the light filters 7, which are alternately introduced into the light flux when the disk 6 rotates and transmits the wavelengths λ_1, λ_2, λ_3 and λ_4. The radiation from the lamp 1' passes through the beam splitter 3, the working cell 5 and the light filters 7. On the photodetector 10 are focused using the lens 9 light pulses having different lengths and carrying information about the absorption of radiation from the lamps 1 and 1' in the cuvettes 4, 5 at the specified wavelengths.

When a certain concentration of one or another concentration of the component appears in the cuvettes 4, 5, the light flux is absorbed at the corresponding wavelengths:

$$\Phi_{1,1'} = \Phi_0\left(e^{-c_i k_i l_1} + e^{-c_i k_i l_2}\right), \tag{5}$$

where Φ_0 – luminous flux from lamps 1 and 1'; c_i – concentration of *i-th* component; k_i – absorption coefficient of the i^{th} component; l_1 – total length of cuvettes 4, 5; l_2 – cuvette length 5.

It follows from equation (5) that at low concentrations of the component to be determined, the light flux from lamp 1 is absorbed. At high concentrations, the radiation from lamp 1 is almost completely absorbed:

$$e^{-c_i k_i l_1} = 0, \tag{6}$$

and the change undergoes a light flux from the lamp 1'.

Thus, it becomes possible to analyze in a wide range of concentrations of the analyte. To increase the selectivity of the analysis and reduce the losses of the light flux, a beam splitter 3 is used, which is an interference light filter that transmits a wavelength and reflects all other wavelengths (λ_1, λ_2, λ_3 and λ_4). Therefore, radiation at wavelength passes only through cuvette 5 (short cuvette for carbon dioxide analysis), and radiation at wavelengths λ_1, λ_2, λ_3, λ_4 – through both cells 4 and 5. This allows the measurement of gas components with significantly different absorption coefficients with high selectivity.

To study the concentration dependences of the device “TAZAL”, calibration gas mixtures prepared in gas cylinders were used. Composition of gas mixtures: “CO+air” or “CO+N_2” and C_3H_8+air” or “C_3H_8+N_2”. The studies were carried out on debugged tuned instruments. Depending on the change in concentration, the transmission value was determined. The measurement results are presented in table 1 and in graphical interpretation.

Table 1. Measurement results.

SGM	Instrument No. 2	Instrument No. 17	SGM	Instrument No. 2	Instrument No. 17
CO+N_2, % об	Tco	Tco	C_3H_8 + N_2, ppm	T_{C3H8}	T_{C3H8}
0	1	1	0	1	1
0,95	0,912	0,917	1420	0,847	0,849
1,79	0,866	0,875	2770	0,732	0,735
4,52	0,784	0,797	3700	0,670	0,673
7,09	0,731	0,745	5050	0,594	0,591
8,95	0,702	0,716			

Note: SGM – supply of test gas mixtures

It was established that the exponential change of the concentration transition has the law of the theory of dependence.

According to the Bouguer-Lambert-Beer law, the type of dependence is as follows [12,13]:

$$T = T_0 \cdot exp(alc), \tag{7}$$

whre T_0, T – transmission before and after passing; a – absorption coefficient; l – absorbent layer length; c – sample gas concentration.

Since the concentrations of the measured gases are quite high, the dependence has deviations from the Bouguer-Lambert-Beer law. The dependence is most accurately described by a cubic equation.

A typical dependence of the CO concentration in nitrogen on the transmission T has the following form:

$$Cco = (1-T)\left[5{,}47653 + (1-T)(26{,}02161 + (1-T)(100{,}7986))\right]. \tag{8}$$

A typical dependence of the concentration of C_3H_8 in nitrogen on the transmission T has the following form:

$$C_{C3H8} = (1-T)\left[8080{,}961 + (1-T)(-201{,}2232 + (1-T)(17604{,}36))\right]. \tag{9}$$

For C_3H_8, the dependence is reproduced well, the characteristics are practically indistinguishable. For dependences on CO, the differences are more noticeable. This means that individual calibration of the scales is required for CO. On calibration gas mixtures ("CO + air", "CO + N_2", "C_3H_8 + N_2", "C_3H_8 + air" or "C_3H_8 + N_2"), studies of concentration dependences were carried out, the results of measurements on various instruments were studied, the scales were calibrated pressure and temperature sensors, as well as an analysis of methods for temperature correction of the readings of the device "TANZAL".

3 Solution of the task

Extreme control of the efficiency of the combustion process can be implemented by applying a signal according to the heat perception ΔP_{pb} and a proportional signal of heat release Q_T depending on the air flow in a wide range of loads. The proposed system of extreme control contains two circuits: a stabilizing internal circuit is formed by a control object and a general air supply regulator, and an external circuit containing an object and a device for extracting the extremum of the target function, maintaining the optimal fuel-air ratio at a constant flow rate of the fuel burned in the furnace. Such a construction of the control system increases the dynamic accuracy of tracking the position of the extremum of the signal ΔP_{ps}, because in the case of a change in fuel consumption, the flow immediately changes to a value close to optimal [4, 14-18]. The extreme regulator eliminates the static inaccuracy of the stabilizing regulator, outputs and maintains the ΔP_{ps} signal in the area of extreme values by influencing the supply airflow.

The effectiveness of the control system under study is characterized by the value of the total losses Π_1 and Π_2 for the search for the extremum:

$$\Pi = \Pi_1 + \Pi_2 = \int_0^{t_1} (y_0 - y(t))dt + \int_{t_1}^{t_2} |\, y(t)\,|\, dt \to \Pi_{\min} . \qquad (10)$$

To check the operation of the system, a program was used that implements the proposed system and in which the step method for searching for the maximum signal ΔP_{ps} was used, the essence of which is to form a control action according to the steepness of the static characteristic of the object. The latter at each step is calculated as the ratio of the differences between the previous and subsequent values ΔP_{ps} and $G_{\text{в}}$:

$$R_I = (\Delta P_{psI} - \Delta P_{psI-1}) / (\Pi_{BI} - \Pi_{BI-1}) , \qquad (11)$$

where R_I – the steepness of the static characteristic of the object at the first step; I – step number.

The algorithm for determining the value of the step change criterion R_{val} has the following form:

$$(G_{\text{в}\max} - n\Delta G_{\text{в}}) \to (OSE \leftrightarrow EMS) \to R_{\text{val}} , \qquad (12)$$

where $G_{\text{в}\max}$ – airflow value corresponding to the maximum static characteristic; $\Delta G_{\text{в}}$ – change in airflow on one cycle of maintaining an extremum; OSE – output step from extremum; [EMS] – extremum maintenance step; n – number of steps from the point (OSE ↔ EMS) to the maximum of the static characteristic.

The numerical values of the steps for maintaining the extremum and R_{val} are determined individually for each object when conducting basic tests and comparing the static characteristics $\eta_b^{\kappa} = f_1(\alpha)$ and $\Delta P_{\text{ps}} = f_2(\alpha)$. The step value is set from the condition that the maximum efficiency of the object falls into the zone of system self-oscillations around the extremum of the statistical characteristic of the object ($\Delta P_{\text{p.s}} = f_2(\alpha)$. An increase in the step of maintaining the extremum leads to an increase in $П_2$ losses. The model of the control system for the efficiency of the combustion process is shown in Fig.2.

The mathematical model of the formation of the random process x_i is selected on the basis of the correlation function $\gamma(\tau)$ obtained from the statistical analysis of signal realizations of the ΔP_{ps} singnal, the evaluation of which is performed according to the following algorithm:

$$R^*(\Delta\tau_j, N) = \frac{1}{N}\left(\sum_{i=1}^{N} P_{ps}(i\Delta t_в)\cdot P_{ps}(i\Delta t_в + j\Delta\tau)\right), \tag{13}$$

where N – number of sample data; $\Delta t_в$ – sample data step; $\Delta\tau$ – discrete process step.

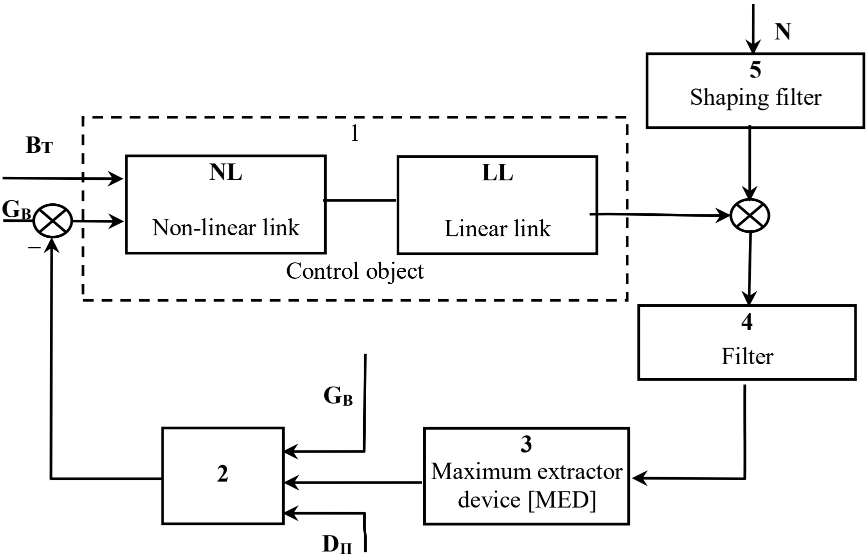

Fig. 2. Model of the combustion process economy control system:
1 – object of regulation; 2 – total air regulator; 3 – maximum extractor device (MED); 4 – discrete exponential smoothing filter; 5 – shaping filter; N – discrete white noise; NL – non-linear link; LL – linear link.

Based on $R^*(\Delta\tau_j, N)$ at $\Delta t_в = \Delta\tau$, the normalized correlation function is calculated

$$(\gamma^*(\tau) = R^*(\Delta\tau_j, N)/D(\Delta P_{ps}), \tag{14}$$

where $D(\Delta P_{ps})$ – output dispersion.

The non-linear link (NL) of the object is a static dependence of the heat perception signal on the air flow rate $\Delta P_{ps} = f(G_в)$ and has the form of a parabola:

$$\Delta P_{ps} = A\cdot(G_в - S)^2 + B(G_в - S) + C, \tag{15}$$

where A, B, C – coefficients determined as a result of testing the object.

The change in air flow is provided within the range from 0 to 100% according to the position indicator (PI) (i.e. $0 \leq S \geq 100$. Linear link (LL) of the object is a transfer function along the channel “air flow $G_в$ – heat absorption ΔP_{ps}”:

$$W(p) = \frac{1}{T_1^2 \cdot p^2 + T_2 \cdot p + 1}, \tag{16}$$

where T_1 and T_2 – time constants determined from the experiment.

The linear part of the object is calculated using the Runge-Kutta method. The numerical values of the coefficients LL and NL are summarized in Table. 2. The formation of interference during simulation modeling was carried out using the implementation of discrete white noise with a dispersion of D_N=100.

Table 2. Parameters of the links of the modeling object and the shaping filter.

Nonlinear link			Line link		Filter	
A	B	C	T_1	T_2	m	N
0,009	1,19	3,04	0,12	9,8	0,3	0,6

To ensure the required ratio between the values of the useful signal and random noise, the value of the coefficient *b* was chosen as follows:

$$b = \sqrt{\frac{R_0 - a_1 R_1 - a_2 R_2 - a_3 R_3}{D_N}} = 1{,}12\ .$$

At the input to the maximum selection device, a discrete exponential smoothing filter was used to filter the noise, the signal of which at the output has the following form:

$$\hat{Y}_i = m \cdot \hat{Y}_{i-1} + n \cdot Y_i,$$

where *m*, *n* – filter parameters (Table 2). The selection of the optimal filter parameters was carried out by direct enumeration of options when the systems operated in three modes: 1) in the absence of interference; 2) in the presence of interference and no filtering; 3) when filtering the introduced noise. The studies were carried out both with a fixed characteristic of the object and with its drift. The numerical values of the dispersions, reflecting the qualitative characteristics of the functioning of the system, are summarized in Table. 3.

Table 3. Simulation results with the drift of the static characteristic of the object.

Operation of the system with interference	Dispersion during the drift of the static characteristic of the object										
	Absent	Vertical BD=0.05 mV/step		Vertical BD=-0.1 mV/step		Horizontal				Combined BD=-0.1mV/step AD=0.2% PI/step	
						AD=0.1 % position indicator [PI] /step		AD=0.15 % PI/step			
	ΔP_{ps} мВ^2	ΔP_{is} мВ^2	$G_в$ УП^2	ΔP_{ps} мВ^2	$G_в$ УП^2	ΔP_{ps} мВ^2	$G_в$ УП^2	ΔP_{is} мВ^2	$G_в$ УП^2	ΔP_{ps} мВ^2	$G_в$ УП^2
Without a filter	2950	2720	431	1390	222	5610	611	16930	1158	16813	1096
With filter	99	171	42	136	24	430	190	2043	356	2317	474

The worst mode of functioning of the system under consideration occurs when the static characteristic of the object under study drifts simultaneously in both horizontal and vertical directions, when the dispersion of the output signal is: $D(\Delta P_{ps})$ = 11585 Pa^2. The advantage of an extremal control system with a variable step in relation to a controller with a constant step of reaching an extremum (CSRE) follows when comparing the dispersion of the output signa ΔP_{is} : $D(CSRE)/D(\Delta P_{ps}) = 930/469 = 1{,}98$. This means that an extreme control system with a signal along ΔP_{ps} and a variable step of searching and maintaining an extremum has a higher quality of control compared to a system with a constant step of reaching an extremum.

4 Conclusion

The physical principles of constructing a primary measuring transducer for the selective measurement of the concentration of harmful substances (CO) and (C_nH_m) in exhaust gas mixtures are substantiated based on the spectrophotometric method of measurement in the absorption bands of the IR range, which ensures selectivity in determining the target parameters. An original combined optical scheme of a three-component (hydrocarbons, carbon monoxide and dioxide) gas analyzer based on the infrared (IR) measurement method has been developed. Furtheromre, a meaningful statement is made and a solution is given to the problems of automatic control of the efficiency of the fuel combustion process as an extremal problem of maximum speed, indicating that the efficiency of the system is characterized by the amount of losses due to the search for the optimum of the statistical characteristic of the dynamic object under study. A comparative analysis of methods for solving problems of extreme control by “increment” and by “second difference” indicates that the performance and quality of regulation is not inferior to the well-known traditional systems for controlling the efficiency of fuel combustion in gas-burning furnaces.

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