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 \( \text{CH}_m \) 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 \( I_{\text{max}} = 4.7 \mu m \)); methane (CH\(_4\)), propane C\(_3\)H\(_8\), and other types of hydrocarbons (3.4 \( \mu m \)), carbon dioxide (CO\(_2\)) (has an absorption band of 4.27 \( \mu m \)).

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:

\[
U = U_0 \exp(-acl) \leq \begin{cases} \frac{\log(0.4)}{0.4343} & \frac{\log}{0.4343} \\ \end{cases}
\]

(1)

where \( a \)-gas mixture flow absorption coefficient; \( U \)-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:

\[
\Delta c/c = \Delta T/T \leq \begin{cases} \frac{\log(0.4)}{0.4343} & \frac{\log}{0.4343} \\ \end{cases}
\]

(2)

or

\[
\frac{\Delta c}{c} = \frac{\Delta T}{T} \leq \begin{cases} \frac{\log(0.4)}{0.4343} & \frac{\log}{0.4343} \\ \end{cases}
\]

(3)
\[ \frac{Sc}{c} = S_{A}/A = \frac{S_{A}}{S_{T}} + A \cdot A_{c} \]

\[ T \cdot A \]

- In which the parameter is detected on the basis of 5 \( \times \) 10 parallel readings;
- \( A_{a} \cdot l \cdot c \)

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 \( \Delta \) 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 \( \times \) 1.2), reaches values in the range (1.35 \( \times \) 1.45);
- The measurement area at \( 0.1A \leq 0.1 \) is unfavorable due to the sharply increasing values of the error \( \Delta \). 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 choose 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 \( C_{n}H_{m} \) (1% vol) take place, the following: their optical densities are quite close \( D_{CH} = 0.48 \) and \( D_{CO} = 0.84 \).

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 \( L_{1} = 3.39 \mu m \) (for hydrocarbons), \( L_{2} = 4.26 \mu m \) (for carbon dioxide), \( L_{3} = 4.6 \mu m \) (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 \( \times \) 4 \( \mu m \)), in which there is no absorption of radiation by any of the gases present in the analyzed mixture, and, therefore, the wavelength \( L_{4} = 3.9 \mu m \) can serve as a reference. To achieve high metrological parameters,
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 $\lambda_1, \lambda_2, \lambda_3, \lambda_4$. 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 component appears in the cuvettes 4, 5, the light flux is absorbed at the corresponding wavelengths:

$$\Phi_{01} = \Phi_1 \left( e^{-c_{1}k_{1}l_{1}} + e^{-c_{2}k_{1}l_{2}} \right)$$

where $\Phi_0$ – 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:
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 ($\lambda_1$, $\lambda_2$, $\lambda_3$, $\lambda_4$). Therefore, radiation at wavelength passes only through cuvette 5 (short cuvette for carbon dioxide analysis), and radiation at wavelengths ($\lambda_1$, $\lambda_2$, $\lambda_3$, $\lambda_4$) – 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+N₂” and “C₃H₈+air” or “C₃H₈+N₂”. 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.

<table>
<thead>
<tr>
<th>SGM</th>
<th>Instrument No. 2</th>
<th>Instrument No. 17</th>
<th>Instrument No. 2</th>
<th>Instrument No. 17</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO+N₂, %</td>
<td>T&lt;sub&gt;CO&lt;/sub&gt;</td>
<td>T&lt;sub&gt;CO&lt;/sub&gt;</td>
<td>T&lt;sub&gt;C₃H₈&lt;/sub&gt;</td>
<td>T&lt;sub&gt;C₃H₈&lt;/sub&gt;</td>
</tr>
<tr>
<td>0.95</td>
<td>0.912</td>
<td>0.917</td>
<td>0.847</td>
<td>0.849</td>
</tr>
<tr>
<td>1.79</td>
<td>0.866</td>
<td>0.875</td>
<td>0.732</td>
<td>0.735</td>
</tr>
<tr>
<td>4.52</td>
<td>0.784</td>
<td>0.797</td>
<td>0.670</td>
<td>0.673</td>
</tr>
<tr>
<td>7.09</td>
<td>0.731</td>
<td>0.745</td>
<td>0.594</td>
<td>0.591</td>
</tr>
<tr>
<td>8.95</td>
<td>0.702</td>
<td>0.716</td>
<td>0.523</td>
<td>0.521</td>
</tr>
<tr>
<td>10.0</td>
<td>0.691</td>
<td>0.703</td>
<td>0.505</td>
<td>0.503</td>
</tr>
</tbody>
</table>

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:

$$T = T_0 \cdot \exp(\text{alc})$$

$$C_{CO} = \frac{1}{1 - T} \left[ \frac{1}{1 - T_0} + \frac{1}{1 - T} \right]$$

$$C_{C_3H_8} = \frac{1}{1 - T} \left[ \frac{1}{1 - T_0} + \frac{1}{1 - T} \right]$$
that individual calibration of the scales is required for CO. On calibration gas mixtures (“CO + air”, “CO + N₂”, “C₃H₈ + N₂”, “C₃H₈ + air” or “C₃H₈ + N₂”), 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 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 $\Delta P_{pb}$ 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 $\Delta P_{ps}$, 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 $\Delta P_{ps}$ 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 $\Pi_1$ and $\Pi_2$ for the search for the extremum:

$$\Pi = \Pi_1 + \Pi_2 = \int_{t_0}^{t_f} (y - y_{Ref}) dt + \int_{t_0}^{t_f} y_{Ref} dt \to \Pi_{min}$$

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 $\Delta P_{ps}$ 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 $\Delta P_{ps}$ and $G_{in}$:

$$R_I = \frac{\Delta P_{ps} - \Delta P_{ps-1}}{\Pi_{BI} - \Pi_{BI-1}}$$

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

$$G_{max} = n\Delta G_s \leftrightarrow OSE \leftrightarrow EMS \leftrightarrow R_{val}$$

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 $\eta_b f$ and $\eta_{ps} 2 (\alpha \Delta P_f \Delta \alpha)$. 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 static characteristic of the object ($\Delta P_{ps} 2 (\alpha \Delta P_f \Delta \alpha)$. An increase in the...
The step of maintaining the extremum leads to an increase in $\Pi$. 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 is selected on the basis of the correlation function obtained from the statistical analysis of signal realizations of the signal, the evaluation of which is performed according to the following algorithm:

$$R(\Delta \tau_j | N) = \frac{1}{N} \left( \sum_{i=1}^{N} P_{ps} \Delta t_i \cdot P_{ps} \Delta t_i + j \Delta \tau \right)$$

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

Based on $R(\Delta \tau_j | N)$, the normalized correlation function is calculated at $\Delta t_i = \Delta \tau$, the output dispersion.

The non-linear link (NL) of the object is a static dependence of the heat perception signal on the air flow rate and has the form of a parabola:

$$\Delta \tau = A \cdot G_a - B \cdot G_a - C$$

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. $0 \leq S \leq 100$.

The linear link (LL) of the object is a transfer function along the channel “air flow $G_v$ – heat absorption $P$”:

$$W(p) = \frac{\Delta P_{ps}}{T_1 \cdot p^2 + T_2 \cdot p + 1}$$

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.

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>m</td>
<td>n</td>
<td>p</td>
</tr>
</tbody>
</table>

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:

$$b = \sqrt{\frac{R_1 - a \cdot R_2 - a \cdot R_3 - a \cdot R_4}{D_N}}$$

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.

<table>
<thead>
<tr>
<th>Operation of the system</th>
<th>Dispersion during the drift of the static characteristic of the object</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertical $BD=0.05$ mV/step</td>
<td>Vertical $BD=-0.1$ mV/step</td>
</tr>
<tr>
<td>Horizontal $AD=0.2%$ PI/step</td>
<td>Combined $AD=0.15%$ PI/step</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>AD=0.1%</th>
<th>AD=0.15%</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta P_{ps}$ mB</td>
<td>$\Delta P_{ps}$ mB</td>
</tr>
<tr>
<td>$G_a$ UП</td>
<td>$G_a$ UП</td>
</tr>
<tr>
<td>$\Delta P_{ps}$ mB</td>
<td>$\Delta P_{ps}$ mB</td>
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<td>$G_a$ UП</td>
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<td>$G_a$ UП</td>
<td>$G_a$ UП</td>
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<tr>
<td>$\Delta P_{ps}$ mB</td>
<td>$\Delta P_{ps}$ mB</td>
</tr>
<tr>
<td>$G_a$ UП</td>
<td>$G_a$ UП</td>
</tr>
</tbody>
</table>

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8
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: $\Delta p = 11585 \text{ Pa}^2$. 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 signal: $D_{\Delta p_{CSRE}} = 930/469 = 1.98 \text{ ps}$. This means that an extremal control system with a signal along $\Delta p$ 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 ($\text{CH}_m$) 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. Furthermore, 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.

References


