Intelligent sensor in control systems for objects with changing thermophysical properties

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Abstract. The control of heat devices in a wide temperature range given thermophysical properties of an object is a topical issue. Optimal control systems of electric furnaces have to meet strict requirements in terms of accuracy of production procedures and efficiency of energy consumption. The fulfillment of these requirements is possible only if the dynamics model describing adequately the processes occurring in the furnaces is used to calculate the optimal control actions. One of the types of electric furnaces is the electric chamber furnace intended for heat treatment of various materials at temperatures from thousands of degrees Celsius and above. To solve the above-mentioned problem and to determine its place in the system of energy-efficient control of dynamic modes in the electric furnace, we propose the concept of an intelligent sensor and a method of synthesizing variables on sets of functioning states. The use of synthesis algorithms for optimal control in real time ensures the required accuracy when operating under different conditions and operating modes of the electric chamber furnace.

1. Introduction

Control of heat devices in a wide temperature range requires consideration of changes in thermophysical properties of the device walls and in the treated products. The examples of such devices are electric furnaces, in which the temperature range of dynamic modes reaches thousands or more degrees.

The systems of optimal control of electric furnaces have to meet strict requirements regarding the accuracy of maintaining operational conditions and energy consumption. These requirements can be satisfied only if the optimal control actions are calculated using the dynamics model, which adequately describes the processes occurring in the furnace.

The dynamics model and the values of its parameters depend largely on thermal diffusivity and heat capacity of the whole set of substances participating in heat transfer processes. The dependence of thermophysical characteristics of various materials on temperature varies considerably. In addition, when operating the furnace, the type and volume of the treated products can vary. This makes it impossible to obtain a single mathematical model of dynamics, ensuring the required accuracy of processes determined by the temperature values of the treated products and other factors.
2. Problem statement
For a large number of situations [1,2] encountered in real operation of the furnace, there are three basic types of energy-saving control problems with restrictions on product quality.

2.1. Problem 1. For the known model of object dynamics

\[ z(t) = A_1 z(t) + B_1 u(t - \tau_1), t \in [t_0, t_k] \]  

(1)

given constraints

\[ \forall t \in [t_0, t_k]: u(t) \in [u_l, u_u] \]  

(2)

\[ z(\bullet) = (z(t), t \in [t_0, t_k]) \in (\bullet) \]  

(3)

it is required to determine the optimal control that transfers the object from the initial state to the final one, i.e.

\[ z(t_0) = z^0 \rightarrow z(t_k) = z^k, \]  

(4)

with a minimum of the functional

\[ J = \int_{t_0}^{t_k} u^2(t) dt, \]  

(5)

here \( z \) is vector of phase coordinates; \( u, u_l, u_u \) are control, the lower and upper boundaries of its change; \( A_1, B_1 \) are matrix of model parameters; \( \tau_1 \) is lag time on the control channel; \( t_0, t_k \) are start and end of the control time interval; \( Z(\bullet) \) is allowable region to change the trajectory of phase coordinates.

Thus, in this problem the array of the original data

\[ R = (A_1, B_1, u_l, u_u, z^0, z^k, z(\bullet), t_0, t_k) \]  

(6)

at the initial time \( t_0 \) is fully known. The solution of problem (1) - (5) according to (6) is performed using the algorithm contained in the knowledge base of the control system [1, 6].

2.2. Problem 2. In contrast to Problem 1, the parameters of the model (1) need to be clarified. Therefore, for the time interval \([t_0, t_0 + \Delta t]\), the control \( u_1(t) \) obtained by solving Problem 1 is used. According to the registered values \( u_1(\bullet) = (u_1(t), t \in [t_0, t_0 + \Delta t]) \) and \( z(\bullet) = (z(t), t \in [t_0, t_0 + \Delta t]) \) the model parameters \( A_1, B_1, \tau_1 \) are corrected. Next, for the new values \( A_2, B_2, \tau_2 \) we find

\[ u_2^*(t), t \in [t_0 + \Delta t, t_k]. \]

2.3. Problem 3. If changes occur in the furnace, for example, in the case of opening the door and increasing (decreasing) the amount of loading, it is necessary to identify the type and parameters of the model (1). Under these conditions, the problem of combined synthesis of optimal control is solved, i.e. on the time interval \([t_0, t_0 + \Delta t_1] \in \Delta t_1 > \Delta t\) the trajectories \( u_1(\bullet) = (u_1(t), t \in [t_0, t_0 + \Delta t_1]) \)  

\[ z(\bullet) = (z(t), t \in [t_0, t_0 + \Delta t]) \]  

are registered; they are used to determine the model type is and to calculate the values of its parameters. Then, for the model obtained we find \( u_3^*(t), \quad [t_0, \Delta t_1, t_k]. \)
3. Methods

To solve the problem of determining the current situation and identifying the type of the problem to be solved, the concept of intelligent sensor (IS) [2,4,7] was used in the system of energy-efficient control of dynamic modes in the electric furnace. Changing situations in the furnace are mainly related to the changes in the range and volume of treated products, opening of the furnace door, accompanied by intense heat exchange with the environment. In addition, process regulations for different types of products provide for significant changes in temperature modes.

The main function of the intelligent sensor is to receive information (output signal) about the possibility of using a “working” dynamics model or the need to correct it, depending on the data received from the group of physical sensors (PS) and from the knowledge base (KB) of the control system [3,4].

The group of PSs making up the lower level of the IS includes three temperature sensors - PST1 (temperature in the vicinity of the treated product), PST2 (temperature in the chamber near the wall), and PST3 (temperature of additionally loaded products), two weight sensors - PSW1 (the weight (mass) of products in the furnace), FSW2 (the weight (mass) of the additionally loaded product), PSτ (the operating time of the furnace with the door open), i.e. the duration of the loading process. Figure 1 shows the layout of physical sensors in the CHO electric furnace.

![Figure 1. Layout of physical sensors in the furnace.](image)

According to its purpose, the IS detects changes in the course of heat transfer processes in the furnace chamber. To fulfill this function the IS performs computational operations with elements of artificial intelligence. Processing of the information from the PS is carried out using the system of production rules. As a result of the processing, one of the following solutions is taken: to save the model without changes, to correct the parameters of the model without changing its form, to perform computational operations to identify the type and parameters of the model. In accordance with the chosen solution, the control device implements one of the following algorithms: calculation of the optimal control (OC) using the previous model of dynamics (Problem 1); solution of a particular problem of combined synthesis of the OC that provides correction of model parameters (Problem 1); solution of the general problem of combined synthesis of the OC, i.e. simultaneous identification of the model of the dynamics of the object and calculation of the OC (Problem 1).

Figure 2 shows a block diagram of an energy-saving control system with an intelligent sensor.
Figure 2. A block diagram of energy-saving control system with intelligent sensor, where CD is a computing device for the IS, ConD is a control device, EM is an executive mechanism, KB is a knowledge base, RS is a reference sensor, PS is a physical sensor, MWS is MiniWebServer.

The use of an intelligent sensor greatly simplifies and simultaneously enhances the ability of the control interface for various situations encountered in the operation of the furnace, and allows developing control systems for a group of devices.

In accordance with the decision made, an algorithm is developed to calculate the control actions implemented by the executive mechanism. The results of this impact are compared with the estimated values.

The algorithmic support of the system was designed and its operability was checked in the FuzzyTECH environment.

Figure 3 shows a variant of technical implementation of the system for a group of electric chamber furnaces. The system provides for recording the temperature inside the chamber and outside the furnace, solving the problems of identifying the model of dynamics and synthesis in real time of energy-saving control actions. The structure of the energy-saving control system includes Miniwebserver (MWS), industrial controller, industrial Ethernet switch, I/O terminal, workstation with expert system.
Figure 3. Technical implementation of the plant by a group of furnaces with a multichannel controller: T11,…, T1n is temperature inside the furnace chamber; T21,…,T2n is temperature outside the furnace chamber; u1,…,un are control actions.

The expert system contains information received from the experts on the analysis of energy-efficient control for specific quadruples, as well as the information on the functions of fuzzy-set accessories, identification algorithms, etc. The database contains information on the results of previously solved problems of energy-efficient control.

A generalized algorithm combining the methods of synthesizing variables and fuzzy logic is used to control furnaces. There is an adaptation mode with automatic correction of model parameters and fuzzy set membership functions; when the adaptation mode is completed, the corrected parameters are recorded into the controller memory for subsequent use.

4. Results and Conclusions
For centralized control of thermal conditions in furnaces, it is possible to combine the hardware and software platform into an industrial Ethernet network, as well as to have access to the global Internet network. This allows for the transfer of data on the furnace group operation or heat treatment sections to an expert system with continuous monitoring and storing of the data, and changing or correcting the heat treatment process in a remote access mode.

The main results of using the intelligent sensor in conjunction with a generalized control algorithm include:
• optimal control of the furnace;
• optimal distribution of tasks (furnace load) by the criterion of energy consumption, i.e. the choice of such a distribution, at which the total energy consumption will be minimal;
• prompt recalculation of the planned task distribution given the changes of industrial situations, including those in the assortment and volumes of manufactured products, process equipment failures;
• full utilization of the accumulated (residual) heat in the furnace during the fulfillment of the planned task, i.e. the control system takes into account the information about temperatures in furnaces and the availability of products expected for heat treatment.

The field of application of the results obtained is quite extensive and is not limited only to electric furnace furnaces. The developed control system is universal, easy to operate, reliable, maintainable, adaptable to tough manufacturing conditions, and has high noise immunity, which increases its reliability in general. This system is also scalable for various enterprise infrastructures based on specific needs.

The broadest possibilities appear when using remote access modes and controlling spatially distributed objects. Remote access significantly increases the scope for large-scale process control. This is especially true for companies that have a number of offices and can easily monitor and manage all the technological processes of their subsidiaries from the headquarters of the parent company.

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