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APPROACHES AND PRINCIPLES FOR ADVANCED CONTROL OF A MULTI-FLOW TUBE FURNACE

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Abstract. To improve the efficiency of multi-flow tube furnaces, a multi-parameter advanced cohesive control system is proposed. Stabilization of the main technological parameter, i.e. the resulting temperature of the output material flow, is carried out by supervisory control of flow rates on the inlet coils, taking into account the existing limitation on the loading of the apparatus, while meeting the requirement of a uniform temperature profile. To create an optimal combustion mode, an additional circuit for regulating the discharge in the radiant chamber of the furnace on the line of atmospheric air supply to the burner registers according to the residual oxygen content in the flue gases is introduced. In the developed simulation model of the control system the possibility of shockless transition between the basic, as in production, and advanced variants of the control system is realized. Transfer functions of the multilink control object, as well as the tuning parameters of the regulators on individual channels are obtained by the built-in tools of Matlab Simulink. Computational experiments on the model showed high speed and control accuracy.

Keywords: multi-flow furnace, cohesive control system, simulation model, temperature profile, efficiency factor

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ПОДХОДЫ И ПРИНЦИПЫ УСОВЕРШЕНСТВОВАННОГО УПРАВЛЕНИЯ МНОГОПОТОЧНОЙ ТРУБЧАТОЙ ПЕЧЬЮ

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Аннотация. Для повышения эффективности работы многопоточных трубчатых печей предложена многопараметрическая усовершенствованная система связного управления. Стабилизация основного технологического параметра — результирующей температуры выходного материального потока, осуществляется путем супервизорного управления расходами на входных змеевиках с учетом имеющегося ограничения на загрузку аппарата, при выполнении требования равномерного температурного профиля. Для создания оптимального режима горения введен дополнительный контур регулирования разряжения в радиантной камере печи на линии подачи атмосферного воздуха к регистрам горелок по содержанию остаточного кислорода в дымовых газах. В разработанной имитационной модели системы управления реализована возможность безударного перехода между базовым, как на производстве, и усовершенствованным вариантами. Передаточные функции многосвязного объекта управления, а также параметры настройки регуляторов по отдельным каналам получены встроенными инструментами Matlab Simulink. Вычислительные эксперименты на модели показали высокое быстродействие и точность регулирования.

Ключевые слова: многопоточная печь, система связного управления, имитационная модель, температурный профиль, КПД

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Introduction

Tube furnaces are the main apparatuses providing thermal regime of technological processes in oil refining and petrochemical industries. Multi-flow tube furnaces are a component of various plants of high-temperature thermos-technological and chemical processes, such as devices for distillation of oil or fuel oil, pyrolysis, catalytic cracking, reforming, hydrotreating, realize heating, evaporation and superheating of liquid and gaseous media [1, 2]. Increasing the efficiency of such apparatuses allows to minimize its consumption, hence, reduces the amount of harmful carbon dioxide emissions into the atmosphere [3, 4]. Implementation of high-tech solutions of industrial automation at the considered apparatus is aimed at optimizing fuel consumption for processing a ton of oil.

A typical control scheme for thermal objects involves regulating the common flow temperature at the furnace output by varying the fuel gas pressure. In production, under the given limitation of the device load, the operator manually sets the same settings for the flow controllers on each coil. As a result, the temperature profile of the output streams is non-uniform, which leads to a decrease in efficiency [2, 4]. The proposed scheme of advanced process control of temperature deviation at the output of the tube furnace coils by the flow rate of the input streams, taking into account the limitation of the apparatus loading will allow the operator to quickly change the value of the flow rate settings and provide a uniform temperature profile (Fig. 1, *a*).

a) *b*)

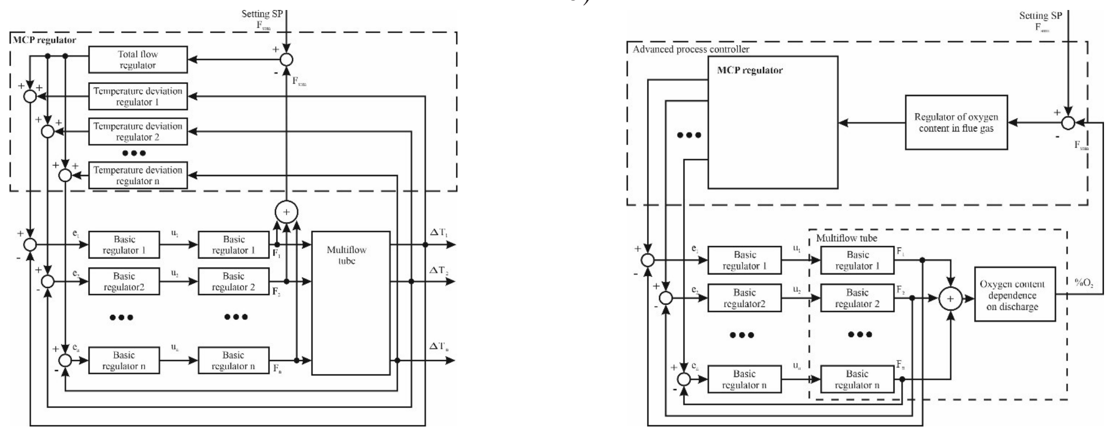


Fig. 1. General structure of control schemes:
a) furnace temperature profile, *b*) residual oxygen concentration in flue gas

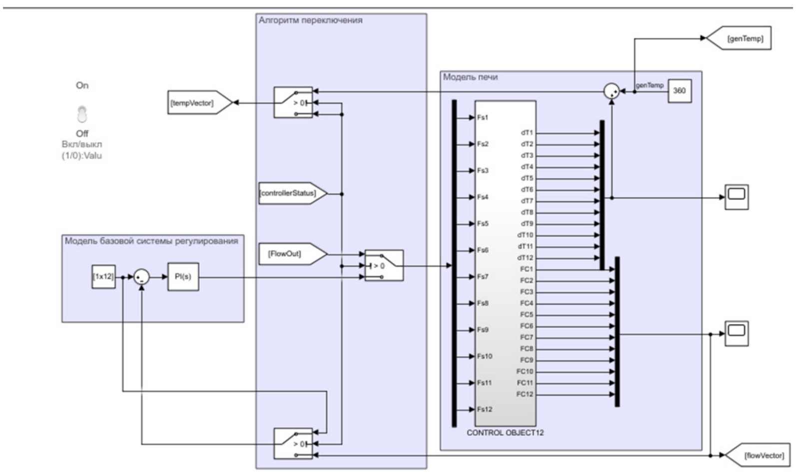


Fig. 2. Simulation model of the control object

Another way to increase the efficiency of the plant is the use of oxygen correction in the flue gases (Fig. 1, *b*). At furnace load of 50% and higher, the oxygen concentration in the flue gases should be from 3% to 4%, which corresponds to the required amount of excess air in the burner for complete combustion of fuel [2, 5]. It has been noted that excess air in flue gases is observed in almost all furnaces operating for more than 15–20 years [1, 2, 6, 7]. This may be caused by improper operation of the burner register or non-tightness of the construction. The maximum efficiency of apparatus is achieved at such excess air, when losses caused by incomplete combustion and heat carried away by flue gases are minimized [2, 6]. Stabilization of oxygen in the flue gases (Fig. 1*b*) will provide optimal rarefaction in the radiant chamber of the tube furnace, and, consequently, will increase the efficiency.

Thus, it seems relevant to develop approaches and principles for advanced control of a multi-flow tube furnace to improve the efficiency of the plant.

Simulation model of the control object

Elements of the simulation model of the technological object (Fig. 2) are united into blocks “Basic control model”, “Switching algorithm” and “Furnace model” by functional feature.

The subsystem "Algorithm of switching" (Fig. 2) contains three switches to set the operation modes of the control system. The high level of the ControllerStatus logic signal satisfies the choice of the advanced variant of the control system. The FlowOut load is used either as a limitation or to calculate vector elements in the "Basic control model" block representing the settings of the flow rate regulators on the furnace input flows.

The subsystem "Furnace Model" describes the dynamics of the channels "temperature deviation – input flow rate". The mathematical model of the technological apparatus depends on the research objectives and complexity of the object under consideration and is formed either on the laws of physics, chemistry, heat engineering and other fundamental sciences [8, 9], or on statistical methods or machine learning methods [10–13]. "Lifetime" of the simulation model is limited due to the instability of physical and chemical parameters of input streams and random impact of the environment, which leads to continuous changes in technical characteristics, as a consequence, the parameters of the object [15, 16]. Taking into account the connectivity of control channels and variation of parameters of the studied technological object, the mathematical model represents a matrix in the following form:

$$W(s)=\begin{pmatrix} W_{11}(s) & W_{12}(s) & \dots & W_{1n}(s) \\ W_{21}(s) & W_{22}(s) & \dots & W_{2n}(s) \\ \dots & \dots & \dots & \dots \\ W_{n1}(s) & W_{n2}(s) & \dots & W_{nn}(s) \end{pmatrix}. \tag{1}$$

Each element in formula (1) describes the effect of the i-th input (flow rate on the i-th flow) on the j-th output (temperature deviations from the set resultant value on the j-th coil) signal. The parameters i and j vary from 1 to n, where n is the number of coils in the design of multi-flow furnace.

Further in the work the object is considered as linear, thus, the expression for the j-th output flow is:

$$W_1(s)=W_{11}(s)+W_{21}(s)+\dots+W_{n1}(s). \tag{2}$$

The structure of transfer functions $W_{ij}(s)$ in the matrix (1) corresponds to the dynamic link of the second order with delay. This is valid for the majority of technological objects [17–19]:

$$W_{ij}(s)=\frac{K_{ij}}{T_{2ij}s^2+T_{1ij}s+1}e^{-\tau_{ij}s}, \tag{3}$$

Parameter K_{ij} is a transmission coefficient at the ij-th control channel. Time constants denotes as T_{1ij}, T_{2ij}, and lag time is as τ_{ij}.

Identification of the parameters K_{ij}, T_{1ij}, T_{2ij} and τ_{ij} in (3) from historical data of the technological process from the plant is performed by various computational methods [12, 14, 17, 18] using the built-in Matlab Simulink tools. It was found that the highest values of the transmission coefficient of about 0.8 have the following control channels: $W_{11}(s)$, $W_{22}(s)$, … $W_{nn}(s)$; for the rest $W_{ij}(s)$ $(i \neq j)$ this parameter varies within ±0.1 [19]. The variation of parameters K_{ij}, T_{1ij} and T_{2ij}, caused by the action of various internal and external factors, was taken into account by introducing additional elements $K_r \cdot r$ and $T_r \cdot r$ in the transfer function. Parameter r sets the permissible limits of variation. This is a random number with a normal distribution law, varying within 0÷1. Thus, in general, the transfer functions for the individual control channels "flow rate – flow temperature deviation" have the following form:

$$W_{ij}(s)=\frac{\left(K_{ij}+K_r r\right)}{\left(T_{2ij}+T_r r\right)s^2+\left(T_{1ij}+T_r r\right)s+1}e^{-\tau_{ij}s}. \tag{4}$$

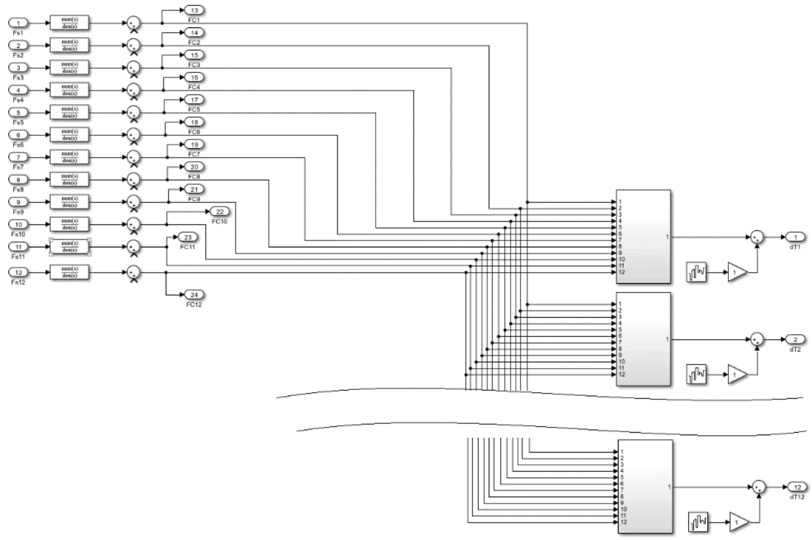


Fig. 3. Structure of subsystem “Furnace model”

Coefficients K_r, T_r calculated based on the accumulated experience of safe and accident-free operation of the plant.

The subsystem “Furnace Model” (Fig. 3) contains groups of elements simulating the dynamics of the flow sensors (block 1), additional outputs to monitor the fulfilment the limitation of the total unit load (block 2), and individual control channels (block 3) in accordance with logic and structure of the model (2), (4).

Advanced process control of a multi-flow tube furnace

The structure of the simulation model of the advanced process control of a multi-flow atmospheric tube furnace develops based on the subsystem “Simulation model of the control object” (Fig. 2) and is shown in Fig. 4.

The resulting temperature of the total flow sets in accordance with the requirements of the technology and regulates in proportional to the ratio of fuel consumption and atmospheric air [1–3, 10]. Based on the temperature data in the total flow at the output of the GenTemp furnace and the temperature vector on individual coils TempVector obtained from the subsystem in Fig. 2, the average temperature deviation dTmean is automatically corrected (Fig. 4). Classical control laws [21–23] were used, which, in comparison with the intelligent control methods, have higher performance [9, 10, 15, 20]. Thus, a PI controller applies in the external loop in the TempBlock subsystem (Fig. 4), the values of the tuning coefficients PI_temp_P and PI_temp_I, as well as the width of the insensitivity zone dzTemp, were calculated using the built-in Matlab Simulink tools. Additionally, protection against the integral oversaturation was implemented in the TempAggrIntegrator1 block of the advanced control system.

The connected flow control loop on the inputs is represented in Fig. 4 by FlowBlock, the regulator is realized as a PI controller with settings: PI_Flow_P, PI_Flow_I and dzFlow. The vector of logical variables FlowModeVector reflects the current structure of the tube furnace (number of operating threads). Zero values of elements correspond to the flow shutdown, for example, for scheduled maintenance. The input signal FlowErrorVector contains the settings either calculated in the external loop TempBlock or set manually by the matrix in the “Basic control model” block (Fig. 2).

Setup of regulators in the internal FlowBlock and external TempBlock1 loops is performed using the built-in Matlab Simulink tools according to the criterion of maximum robustness of the system. There is

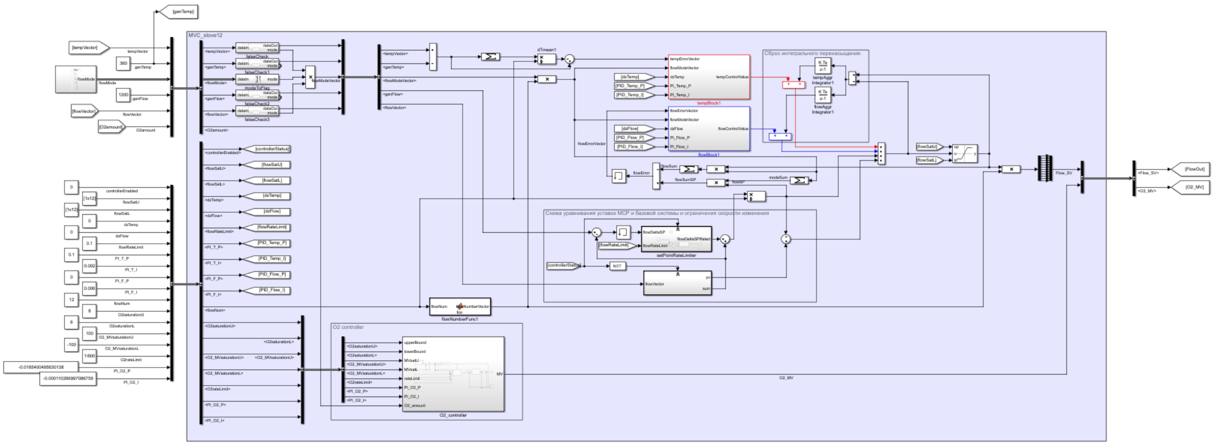


Fig. 4. Simulation model of the advanced process control of the multi-flow atmospheric tube furnace

a possibility to exclude some flows Block “Object Structure” (Fig. 4), which is in demand, for example, during maintenance of automation equipment on a particular coil.

In addition, shockless switching between variants of the control system (Fig. 4) of a multi-flow tube furnace implements due to equalizing the settings. Low level of the ControllerStatus logic signal returns the system to the basic variant of control. Then, the current value of the total unit load, calculated in the subsystem “Furnace Model” (Fig. 3, block 2) of the advanced system, is memorized. After that, the settings of the flow controllers for each flow are calculated in the block Shockless_Switching.

The setPointRateLimiter subsystem (Fig. 4) sets a limit on the rate of change of settings by the built-in Matlab function. It generates an output signal equals to the difference between the current value of flow rates and settings for individual flows in the advanced control system. The memory element eliminates errors during the model simulation run. In addition, the absolute value (Saturation block) on the upper or lower limits (flowSatU or flowSatL) of the settings is limited. Reaching these values activates the reset aggravation function “Reset integral oversaturation” (Fig. 4).

The internal structure of the “O2 controller” subsystem is shown in Fig. 5. The concentration of residual oxygen in the flue gases (O2 amount signal) has a long lag time. Therefore, a “gating” signal is supplied to the “O2 Block” to stop the control process, when the output parameter reaches the UpperBound or LowerBound values.

The maximum permissible values of the discharge in the radiant chamber of the tube furnace MVsatU and MVsatL are the parameters of “O2 Block” regulator. This feature is critical for the considered apparatus. Both the absolute value of the setting MeanErr and the rate of its increase RateLimit forms in the “O2 Rate” block. The control actions on the gate valves in the atmospheric air supply line to the burner registers are discrete signals.

Approbation of the advanced process control

The effectiveness of the proposed approaches and principles of the advanced process control of the multi-flow tube furnace was evaluated by means of model tests, the results of which are presented in Fig. 6. It was required to estimate the stability of the transient process for the basic and proposed control systems, and to calculate the control quality indicators, in particular, performance and accuracy.

Transient graphs (Fig. 6, *a*), obtained when switching the control system from the basic to the advanced scheme at 2600 seconds, demonstrates the narrowing of the range of temperature variation of individual streams and the establishment of the set value of the resulting temperature after 1400 seconds. The flow rates of the input streams dynamically change, taking values within (89÷91) m^3/h, which is

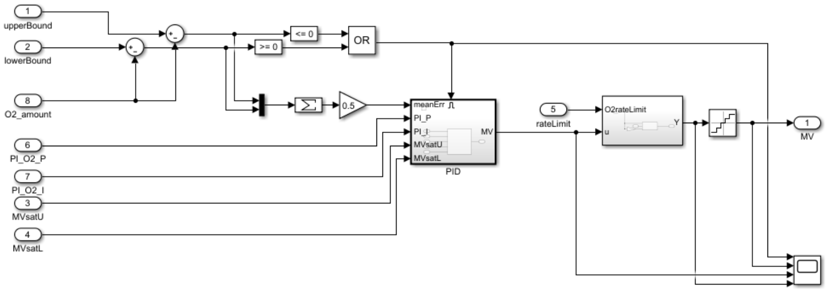
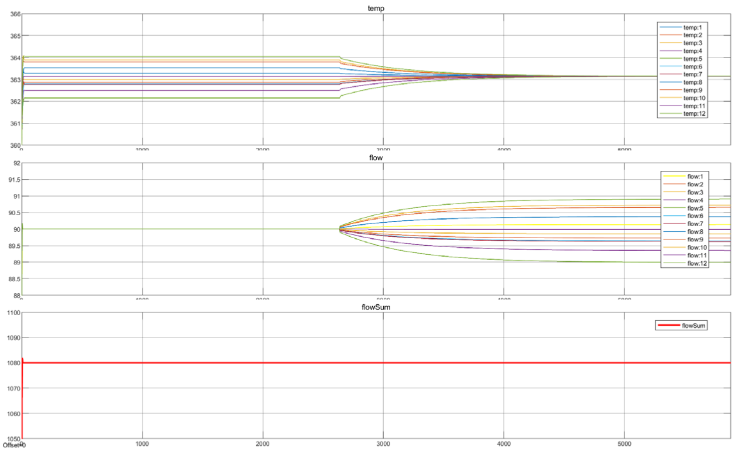


Fig. 5. Structure of “O2 controller” subsystem

a)



b)

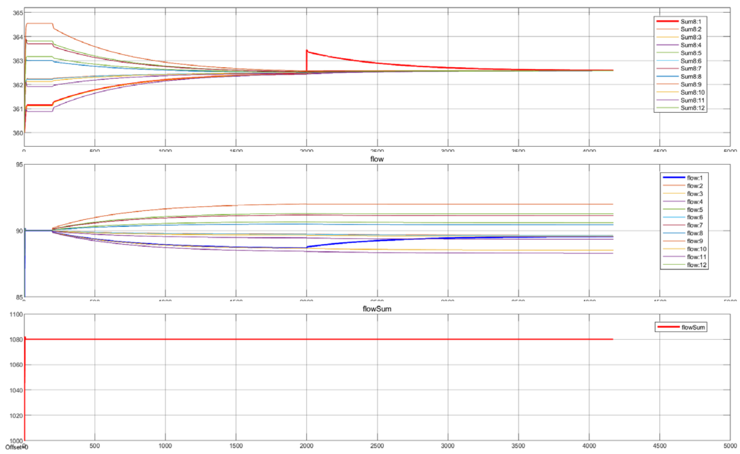


Fig. 6. Results of model tests of the control system:
a) when switching between variants of control systems, *b*) when perturbation is applied

allowed by the technological regulations. The furnace load volume for both control schemes remains constant at 1080 m^3/h.

The output signal of the model, when a temperature perturbation (1° increase compared to the calculated one) arrives at the first coil at 2000 seconds, quickly reaches the set steady-state value, and the static error equals zero. The temperature deviation is compensated after 700 seconds (Fig. 6, *b*). Numerical experiments performed on the simulation model of the system of advanced process control of a multi-flow tube furnace allows to conclude that the performance results are satisfactory in terms of control quality.

Conclusion

Improved efficiency of the multi-flow atmospheric furnace of the oil refining apparatus is achieved by implementing the proposed approaches and principles of advanced process control. The uniform temperature profile of the output flows indicates the optimality of combustion conditions in the radiant chamber.

The mathematical model of control object dynamics developed taking into account connectivity and random variation of technical parameters of control channels to improve its accuracy and “lifetime”. Another advantage of the proposed approach is the scalability of the simulation model, which allows to manually exclude part of the flows from the analysis. The change in the control object structure is compensated by the random component in the transfer functions of each channel. This principle is especially demanded, when the object is operated in continuous production. The system of advanced process control provides compensation of integral saturation of regulators, robustness to small fluctuations of technical parameters of the control object, and realizes the “gating” mode on the channel of residual oxygen in flue gases.

Thus, the implementation of the proposed approaches and principles of advanced process control of the multi-flow tube furnace of oil refining apparatus will increase the coefficient of utilization of the heat of combustion of fuel, decrease the volume of fuel consumed, as a consequence, reduce harmful carbon dioxide emissions into the atmosphere.

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