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OPTIMIZATION OF COMBUSTION CONTROL IN INDUSTRIAL FURNACES

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ABSTRACT

The control of combustion processes largely determines the efficiency of the fuel facility, and hence the environmental pollution caused by it. An optimization of the control of combustion processes in industrial plants is proposed, covering the static regime of almost inertial chemical transformations and the dynamic regime of inertial heat transfer in the combustion chamber.

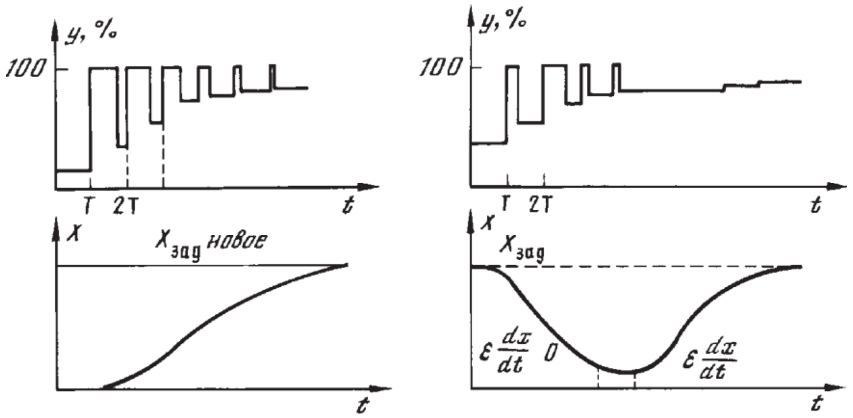
Keywords: combustion processes, optimization criteria, minimum fuel consumption, consumption of recirculating flue gases.

INTRODUCTION

In the coming decades, combustion processes will remain almost the only way to use fuel energy, while at the same time being one of the main sources of environmental pollution. Only in ferrous metallurgy, during the production of a ton of steel, about 2500 cubic meters of harmful products are emitted into the atmosphere [1]. According to forecasts, at the end of this century in industrial areas, which make up 10% of the total land, the permissible norms of environmental pollution will be exceeded. At the same time, combustion processes are not efficient enough to convert the chemical energy of the fuel into heat. There is a significant reserve of industrial combustion plants, which can be realized by optimizing the control of combustion processes. Optimization of combustion process control in industrial plants is a modern approach to solving environmental problems related to their operation. Indeed, when optimizing the control of combustion processes according to the energy criterion with the limitation of harmful emissions in flue gases, on the one hand, environmental combustion of fuel is achieved, and on the other hand, the maximum amount of energy is obtained from a unit of fuel, which leads to a decrease in fuel consumption per unit of production. This means reducing environmental pollution [2] and to some extent solves the problem of preserving the world's limited reserves, non-renewable energy sources.

CHARACTERISTICS OF COMBUSTION PROCESSES

Any combustion process as an object of control can be depicted using a structural diagram (Fig. 1, **a**). Adjustable values are the temperature in the combustion chamber θ and the air flow coefficient α.



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that the fuel consumption F_t will be the driving parameter, and the air consumption F_b will be the slave. In principle, this choice is of no fundamental importance. The object presentedin that way along the separate channel $\theta - F_t$ and by the cross-link $\theta - F_{in}$ has a significant inertia, predetermined by the heat exchange occurring in the combustion chamber. Through another separate channel $\alpha - F_{in}$ and the cross-link $\theta - F_t$ the object is almost inertialess due to the instantaneous mixing of air with the furnaceand its combustion. This feature of the combustion process as a process of chemical transformations , accompanied by intensive heat exchange in the combustion chamber, determines the criterion and type of optimization. This criterion is energy, and for an inertia-free separator channel $\alpha - F_{in}$ only static optimization makes sense, and for an inertial separator channel $\theta - F_t$ – dynamic.

OPTIMIZATION CRITERIA

Static optimization. For the vast majority of cases, static optimization of combustion processes can be expressed by the following objective function:

$$(1) \qquad J_1 = \sum_{i=1}^{3} Q_{\text{п}i} \to \min,$$

and limitations

$$(2) \qquad \theta_{\text{н}} \leqslant \theta \leqslant \theta_{\text{в}}; \quad \alpha > \alpha_{\min}; \quad \sum_{j=1}^{n} \frac{c_j}{c_{j\text{доп}}} \leqslant 1,$$

where Q_{pi} is the heat loss (losses due to mechanical Q_m and chemical Q_x underburn of fuel and losses associated with the exhaust flue gases Q_{dg}) accompanying any combustion process, θ_n and θ_b are respectively the lower and upper values of the combustion temperature, which are determined by the requirementsimposed on normal the course of the combustion process in order to avoid endothermic reactions associated with heat absorption; α_{min} is the minimum value of the air flow coefficient below which combustion cannot be carried out ($\alpha_{min} < 1$); c_j and c_{jdop} are the concentration and permissible concentration of the j-th harmful component in the gases, respectively. We will call (1) the criterion of heat loss. For some special cases, for example, for heating metal blocks in a flame furnace, the objective function should include the loss of oxidized metal, since the resulting scale is a function of the ongoing combustion process. This objective function, called the criterion of minimum total losses during combustion processes, is discussed in [3] and is not the subject of this article.

Implementation (1) is carried out in the following sequence. Dependencies are defined for each combustion plant

$$Q_{\text{п}i} = f(\alpha), \text{ а затем } \sum Q_{\text{п}i} = f(\alpha)$$

(an example of similar dependencies for the objectdescribed in Fig. 1,a, representingflax in Fig. 1,b). Let's define the value of the $\alpha_{\text{the opt}}$ in which criterion (1) is met. Since it is difficult to apply for control purposes, the air flow coefficient α is uniquely related to the oxygen content ofO_2 in the exhaust flue gases through the so-called oxygen formula

$$(3) \qquad \alpha = \frac{21}{21 - \text{O}_2},$$

then instead of $\alpha_{\text{wholesale}}$ it is recommended to use $\text{O}_{2\text{opt}}$ obtained from (3) when $\alpha = \alpha_{\text{wholesale}}$. It is also known that with different loads on the combustion plant, the α_{opt} and the corresponding $\text{O}_{2\text{opt}}$ change. This dependence can be determined for each combustion installation. It turns out that when performing (1) the flow rate of the who $\alpha > 1$, i.e. the second constraint of (2) that ensures the combustion process is always met. If we assume that the left part of the first inequality of (2) can be preheated by preheating the air, then the right part of this inequality and the third constraint of (2) are fulfilled in controlling the combustion process. Since $\alpha_{\text{wholesale}} > 1$, the harmful components in flue gases consist mainly of sulfuric and nitric oxides and ash (carcinogenic products and CO in flue gases at $\alpha > 1$ are present in negligible quantities). If the problemof sulfuric oxides is solved by pre-treatment of fuel or with the helpof modern sulfur-cleaning facilities, which can be equipped with any combustion plants, and the problem associated with ash, with the help of electrostatic precipitators, cyclones, etc., then the exclusion of nitrogen oxides from flue gases is still remains a major challenge. This paper proposes a solution based on lowering the combustion temperature by recycling flue gases, with emissions of nitric oxides below permissible standards. Reaching the combustion temperature below θ_{B}

$$(4) \qquad \text{O}_{2\text{рзад}} = \frac{21 F_{\text{в}} \text{O}_{2\text{зад}}}{21 F_{\text{в}} - F_{\text{р}} \text{O}_{2\text{зад}}},$$

(corresponding to about 180⁰C, with nitric oxide emissions severely underestimated) by recycling part of the flue gases in the combustion chamber requires a change in the α O2 content in them in such a way that criterion (1) is met. We obtained a dependence, which determines the specified value of the oxygen content in flue gases $\text{O}_{2\text{rzad}}$ during their recycling:

$$(5) \qquad J_2 = \int_0^{t_{\text{п}}} |F_{\text{т}}(t)|\, dt \to \min$$

where F_c is the air flow rate supplied for the combustion process, O_2 is the oxygen concentration in flue gases calculated from (3) without recirculation at $\alpha = \alpha_{wholesale}$, F_p is the flow rate of the recirculating flue gases.

Dynamic optimization. Dynamic fuel consumption optimization of combustion processes [4] implements the criterion when limited

$$(6) \qquad |F_т(t)| \leqslant M,$$

where M is the maximum value of fuel consumption. Implementation (5) achieves a transition from one state of a thermal object (combustion chamber) to another in time t_n with the lowest fuel consumption. In the work [5], using the Pontryagin principle [6], it is proved that for a linear object of the nth order, the fuel-optimal control effect depending on the initial and boundary conditions has the following form.

$$(7) \qquad F_т(t) = \{M, 0, -M, 0, M \ldots\} \text{ или } F_т(t) = \{-M, 0, M, 0, -M \ldots\},$$

i.e. the optimal fuel consumption control action is a piecewise function that takes both limit values ±M, separated by an interval in which the control effect is zero. The number of switchings of the control action depends on the order of the object, the initial and boundary conditions, the duration of the transition process, but their maximum number should not exceed n − 1. Dependence (7) refers to cases where the duration of the transition process is previously fixed. With zero initial conditions and a non-fixed transient duration, it is proved that the optimal control according to (5) is as follows:

$$(8) \qquad F\,т(t) = \{M, 0\} \text{ или } F\,т(t) = \{-M, 0\}.$$

[3] proves that for the same object under zero initial conditions and the same boundary conditions, the control of the type (8) at anunfixed duration of the transient process provides an absolute minimum of fuel consumption. However, for optimal fuel consumption transients under control actions of type (7) and a pre-fixed duration of these processes, fuel consumption may be increased. It turns out that that for a particular object under zero initial and specified boundary conditions there is only one duration of the transient process T_{opt}, in which the control effect of the type (8) is optimal in terms of fuel consumption, i.e. fuel consumption is minimal. At any other duration ($T < T_{opt}$ or $T > T_{wholesale}$) the control effect of the type (7) will also be the optimal fuel consumption effect, but the fuel consumption is increased. Such a duration of the T_{opt} process approaches the duration of optimal transient processes. Thus, the ratio (8) provides an answer to the conflicting requirements for the speed and energy efficiency of control in the case of zero initial conditions, which for combustion processes in industrial installations can be considered usual. For this case, the duration of the T transient process and the switching point T_n for a 2nd order static object, one can analytically define a system of transcendental equations:

$$(9) \qquad \begin{cases} T = T_1 \ln \dfrac{k_0 M(e^{T_{\text{п}}/T_1} - 1)}{x_y} \\ T = T_2 \ln \dfrac{k_0 M(e^{T_{\text{п}}/T_2} - 1)}{x_y} \end{cases},$$

where k_0, E_1 and T_2 are the parameters of the object, x_y is the difference between the old and the new values of the adjustable coordinate. Finding a similar (9) dependence for an object of the nth order is extremely difficult. Analyzing (7), we come to theconclusion about the practical unrealizability of the optimal fuel consumption control. This is true only for static objects. [3] it is proved that in the sphereof astatic objects for which the optimal problem is degenerate, under theleft initial conditions, to obtain the optimal fuel consumption control is sufficient so that the control effect during transient processes does not change its polarity and that the main coordinate has an aperiodic the nature of the change. Indeed, when implementing (7), if we assume that +M is a coolant (fuel), then −M is a coolant (cold agent), which does not make sense for the combustion installation. The ratio (8) does not contain such an abbreviation, but if the analytical dependence of the vi-da (9) is known for an object of the nth order, then the change in the parameters of real thermal objects makes it very difficult to perform. However, finding a theoretically optimal control type (8) in terms of fuel consumption makes it possible to disclose its main characteristics and evaluate, naskolko bliz ko k optimalnomu kaj doe up ravlenie, obladayusche timi harakte ristics. The qualitative characteristics of the fuel consumption-optimal control type (8), which under zero initial conditions (thermal regimes in industrial combustion plants as control objects are characterized by a low frequency of disturbing influences applied to them, which is why the adoption of zero initial conditions of transient processes correctly) provides an absolute minimum of fuel consumption with simultaneously good performance, are expressed in the following.

1. The optimal control effect in terms of fuel consumption in transient processes does not change its polarity.
2. At the beginning of each transient process, the optimal fuel consumption forcing effect is of a forcing nature.
3. In transient processes, the main controlled coordinate has the aperioditic character of change.

Based on these basic features of optimal fuel consumption control, it is possible to synthesize quasi-optimal algorithms and control structuresfor combustion processes in industrial enterprises.

CONCLUSION

The proposed optimization of the control of combustion processes according to the energy criterion in industrial installations is as follows.

1. Control during the combustion process by a driven parameter (a parameter associated with almost inertia-free chemical transformations) ensures ecological combustion with minimal heat losses, regardless of the load on the combustion plant and the temperature at the combustion site. In flue gases, harmful emissions of carcinogenic products, carbon

monoxide and nitrogen will be below permissible standards. This control is implemented on the basis of information on the load on the combustion plant, the temperature at the place of combustion and the oxygen content in the exhaust flue gases. The real energy savings are 5-8%.

Thus, the proposed optimization of combustion control in industrial installations as a whole achieves more than 10% fuel economy, while emissions of carcinogenic products, carbon monoxide and nitrogen in flue gases are below permissible standards. In addition, emissions of oxides of sulfur, ash and carbon dioxide are reduced by a percentage of realized fuel savings. Experience shows that investments to implement such optimization pay off in less than a year.

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