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EXPERIMENTAL AND INDUSTRIAL METHOD OF SYNTHESIS OF OPTIMAL CONTROL OF THE TEMPERATURE REGION OF CUPOLA MELTING

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Abstract

The object of research is the temperature regime of melting in a cupola. The synthesis of optimal control of such an object is associated with the presence of a problem consisting in the complexity of its mathematical description and the absence of procedures that allow one to obtain optimal control laws. These problems are due to the presence of links with a pure delay, non-additive random drift, and difficulties in controlling the process parameters, in particular, accurately determining the temperature profile along the horizons and the periphery of the working space of the cupola.

The proposed conceptual solution for the synthesis of optimal temperature control allows the use of two levels of control: the level controller solves the problem of maintaining the constant height of the idle charge, and the problem of increasing the temperature of cast iron is solved by controlling the air supply to the tuyere box.

It is shown that the problem of regulating the upper level of an idle charge can be solved by reducing the model of the regulation process to a typical form, followed by the use of the Pontryagin maximum principle.

A procedure for the synthesis of optimal air flow control is proposed, which makes it possible to obtain the temperature regime control law on the basis of experimental industrial studies preceding the synthesis process. This takes into account the time delay between the impact on the object and its reaction, which makes it possible to predict the temperature value one step acharge, equal to the time interval during which the lower surface of the fuel charge reaches the upper surface of the level of the idle charge.

A procedure for temperature profile control based on the use of D-optimal plans for selecting sensor installation points is proposed. Due to this, it becomes possible to determine the temperature profile of the cupola according to its horizons and the periphery of the working space of the cupola with maximum accuracy.

The proposed synthesis method can be used in iron foundries equipped with cupolas, as it is a tool for studying a real production process, taking into account its specific conditions. This will allow developing or improving control systems for cupola melting, implementing different control modes: manual, automated or automatic.

Keywords: cupola melting, temperature control, Pontryagin maximum principle, level controller, idle charge, fuel charge, air consumption, tuyere box.

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1. Introduction

Serial production of castings for machine-building purposes requires high productivity in the production of cast iron, as the main material for machine-building parts, justified by a good combination of strength, performance and casting properties. The lack of opportunities to use only pure charge, combined with the requirements of high productivity, predetermines the need to use cupolas in foundries of machine-building enterprises. Therefore, despite the well-known problems generated by cupola melting, for example, environmental hazards, it is problematic to abandon this process at this stage. It is cupola melting that makes it possible to obtain cast iron in large quantities with such quality indicators that are acceptable for the manufacture of machine body parts while minimizing the cost of their manufacture [1, 2].

In an effort to reduce the negative factors in the use of cupolas and to ensure acceptable melt quality indicators, researchers are moving towards improving melt control processes by choosing certain control quality criteria. Among them, the criteria for maximum intensification of the process [3, 4], an adequate technological description of the process [5], a reasonable choice and rational layout of technical means and the structure of the control system [6, 7], and achieving the effect of environmental safety [8] can be distinguished.

The choice of individual criteria for the quality of control as a priority allows to practically solve local production problems, however, from the point of view of scientific problems, the problem of compromise optimization remains. From a practical point of view, there remains the problem of providing other requirements that form other quality criteria. This is justified by the fact that individual quality criteria compete with each other and in real conditions it is necessary to choose a priority one, obviously going to worsen others that are not so important. For example, by choosing performance indicators as priority indicators, it is possible to obtain a melt of lower quality in terms of composition and properties. This is justified, since subsequent technological methods can offset the deterioration of the cast iron quality criteria. For example, by choosing the optimal chemical composition in terms of mechanical strength [9], the composition of the charge can be selected, as well as modifiers that reduce the risk of Fe_3C formation [10]. The choice of modifiers is an inexhaustible area of research, however, the ultimate goal of such a choice is to meet the requirements of a particular production for obtaining castings of high quality in terms of microstructure. If melting is carried out in cupolas, then in addition to modification, it is necessary to apply measures that increase the mechanical properties of cast iron. This is due to the fact that cupola iron has an increased carbon content, which leads to a decrease in tensile strength, as the main required mechanical property. For this, technological methods of combining modification with alloying can be used [11–14]. By selecting the optimal combinations of alloying elements, it becomes possible to improve the mechanical characteristics of cast iron [15, 16]. This forms rational technological modes of processing the cast iron melt outside the furnace [17], which have the potential for optimization. For such optimization, mathematical models of the «composition-properties» type are built [18], choosing as an optimization criterion the one that is the most important from the point of view of operational requirements – for parts of internal combustion engines [19], mixer blades and other mechanical engineering parts [20–22].

Thus, a compromise in relation to the control of cupola melting, in terms of the choice of the quality functional, is achieved as follows: priority is given to those criteria that are directly related to the implementation of the cupola process, and the quality of the metal is ensured by out-of-furnace processing. Among the priorities are productivity, environmental indicators of smelting, resource and energy consumption.

If to consider the same criteria, but within the framework of a more general system, for example, a foundry, then it becomes necessary to use cupolas in conjunction with other foundry units, for example, electric arc furnaces [23] or induction furnaces [24, 25]. In this case, the control possibilities are expanded, since the secondary unit makes it possible to eliminate the disadvantages of the cupola furnace in terms of ensuring the quality of cast iron. In addition, with the optimal control of the secondary unit, a reserve for saving energy resources as a whole arises, since their costs are a common part of the energy costs of the foundry, which are included in the cost of castings. In this case, the control task is expanded to the level of control of the duplex smelting process [23], which requires considering the control object as a combined electrotechnological complex [26, 27] integrated with the cupola complex and other equipment of the foundry. In this case, integration into a common technological flow allows to represent the cupola process as part of the general technological process for manufacturing castings, considered from the standpoint of an organizational and technical queuing system [28]. It is natural to assume that with such an approach, all temporary operations of the processes must be coordinated. That is, the prevention of downtime, in particular due to the lack of metal of the required quality, can be achieved by optimally distributing the execution of technological operations and resources for their implementation [29, 30]. The latter may include energy costs.

However, it should be noted that the determining factor in this entire chain is the temperature of the melt. This is due to the fact that the temperature must ensure the quality and completeness of the redox processes in the melt, as well as the ability to fill the required number of molds for the required time interval. Otherwise, the temperature becomes a factor limiting the entire technological process. In addition, the subsequent technological modes of out-of-furnace processing or melt processing in the secondary unit depend on temperature, if melting is carried out by a duplex process. Consequently, the control of cupola melting should provide a given stable temperature regime of melting, since it is on it that the efficiency of the entire further technological process of casting production depends.

The object of research is the temperature regime of cupola melting. The hypothesis of the study is the possibility of synthesizing the optimal control of the temperature regime of cupola melting, as an object that has links with a pure delay and is subject to non-additive random drift, considering the control problem as a task with speed. At the same time, it is assumed that it was possible to conduct an experimental-industrial study of the behavior of the control object, with the aim of determining its dynamic characteristics directly on the functioning cupolas in real time. An experimental-industrial method for the synthesis of temperature control is proposed, which makes it possible to stabilize the temperature of cast iron at the maximum possible value, due to two levels of control: by regulating the height of the idle charge and by controlling the air supply to the tuyere box. The principle of temperature control along the horizons of the cupola proposed within the framework of this method makes it possible to estimate the position of the temperature profile with maximum accuracy, both along the height and along the periphery of the working space of the furnace.

2. Materials and Methods

Considering the problem of temperature control as a problem of speed, a reasonable research method is the use of the Pontryagin maximum principle. This principle is applicable to search for the optimal control of objects described by systems of linear or nonlinear differential equations for a wide range of applications: control of technological processes [31–33], transport [34–37], when designing structures in the energy sector [38, 39]. It should also be noted that the principle itself continues to be actively developed within the framework of the general control theory: studies of transversality conditions [40–42], control of systems with discrete time, impulsive control with mixed constraints [43, 44], for control problems on an infinite interval [45, 46]. Based on the description of the control object, the application of the maximum principle was studied at two levels:

– to regulate the level of the idle charge,

– to control the flow of air supplied to the tuyere box.

3. Results and discussion

3. 1. Conceptual solution for the synthesis of optimal control

Fig. 1 shows the visualization of the temperature profile of the cupola furnace by loading zones. The following designations are accepted:

H – the horizon level along the height of the cupola, mm;

h – the current coordinate along the height of the cupola, mm;

h_{sh} – the horizon along the height of the cupola, corresponding to the position of the upper level of the idle charge, mm;

$h_{sh\,max}$ – the maximum horizon along the height of the cupola, corresponding to the maximum position of the upper level of the idle charge, mm;

$h_{sh\,min}$ – the minimum horizon along the height of the cupola, corresponding to the minimum position of the upper level of the idle charge, mm;

Δh^{+} – positive deviation of the upper level of the idle charge along the horizon, mm;

Δh^{-} – negative deviation of the upper level of the idle charge along the horizon mm;

T – the temperature in the cupola, °C;

T_{iron} – hot iron temperature at cupola tapping, °C.

The temperature profile in the combustion and melting zone has the form of a parabola. Accordingly, the temperature profile along the height of the idle charge also has the form of a parabola. If the upper level of the charge charge drops to $h_{sh\,min}$ or rises to $h_{sh\,max}$, this leads to a shift in the temperature profile (**Fig. 1**). A temperature difference $\Delta T|_{h \neq h_{sh}}$ is formed on the horizon of the cupola, which corresponded to the nominal position of the upper level of the idle charge (in **Fig. 1**, this difference, as well as the position of the shifted temperature profile, are shown conditionally).

The selected control should return the temperature profile to the set position by the combined effect of this temperature regime: by changing the amount of coke in the idle coke (V_c) and by changing the flow rate of blown air (Q).

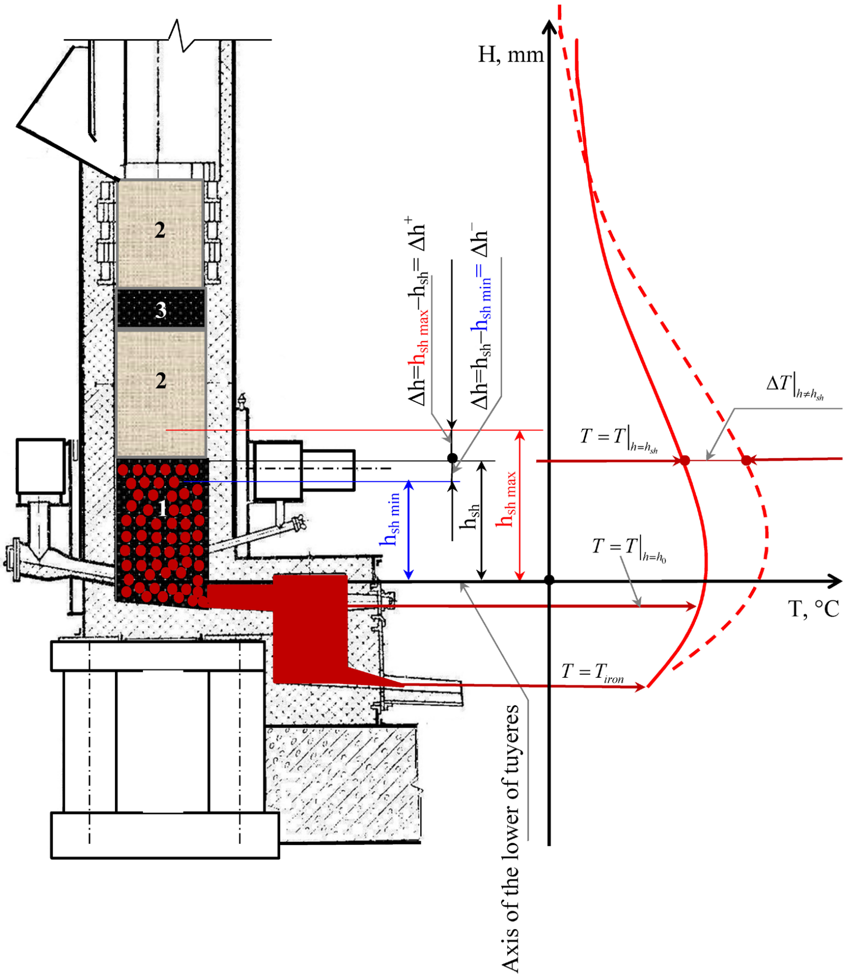

Fig. 1. Visualization of the temperature profile of the cupola furnace by loading zones (built on the basis of using the image from [23]): 1 – idle charge; 2 – metal charge; 3 – fuel charge

As the first control action (u_1), the control of the fuel charge loading is chosen. This choice is due to the fact that a decrease in the height of the idle charge leads to a decrease in the temperature of the cast iron, caused by insufficient contact time of the melt with the coke of the idle charge (**Fig. 2**):

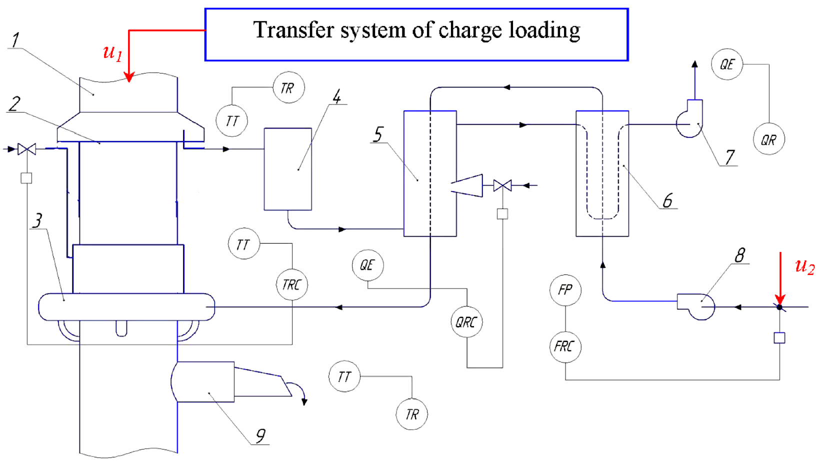

Fig. 2. A simplified scheme for controlling the process of cupola melting (built on the basis of using the image from [23]): 1 – cupola; 2 – spark arrester; 3 – tuyere belt; 4 – wet cleaner; 5 – radiation recuperator; 6 – convective heat exchanger; 7 – smoke exhauster; 8 – fan; 9 – forehearth

As the second control action (u_2), let's choose to control the position of the damper on the pipeline supplying air to the tuyere box. This choice is due to the fact that an increase in the volume of injected air intensifies the combustion process, thereby increasing the temperature of the gases in the furnace as the main heat carrier for melting the metal charge. This factor of intensification of cupola melting is the most applicable in practice (**Fig. 2**).

The dependence of the cast iron temperature on the volume of the idle charge, estimated by the consumption of coke for melting, has a non-linear form. This is due to the fact that the increase in temperature due to the increase in coke consumption is limited by the quality of the coke and the physicochemical processes that develop in the coke layer during combustion and contact with the melt.

The dependence of cast iron temperature on the volume of injected air also has a non-linear form. This is due to the fact that the increase in temperature due to an increase in the volume of injected air is limited both by physicochemical processes in the combustion zone and by aerodynamic resistance, in particular, from the side of the charge column in the cupola.

Given that both factors affect the gas temperature in the cupola, forming a specific temperature profile, on which the iron temperature at the outlet depends, the iron temperature can be represented by the equation:

$$T_{iron} = a_0 + a_1V_c + a_2V_c^2 + a_3Q + a_4Q^2 + a_5V_cQ. \quad (1)$$

The choice of such an equation structure is due to the limited scope of the input variables, which makes it possible to assume the possibility of obtaining adequate regression equations in the form of a polynomial of the second degree.

If the height of the idle charge is maintained constant, then $V_c = \text{const}$ and equation (1) takes the form:

$$T_{iron} = b_0 + (a_3 + a_5V_c)Q + a_4Q^2, \quad (2)$$

where

$$b_0 = a_0 + a_1V_c + a_2V_c^2. \quad (3)$$

Then, by changing the damper position on the pipeline supplying air to the tuyere box, it is possible to provide such an air supply at which $T_{iron} \to T_{iron\,max}$ max, and determined from the condition:

$$\frac{dT_{iron}}{dQ} = b + 2a_4Q = 0, \quad (4)$$

if to introduce the notation $b = a_3 + a_5V_c$.

Thus, the task of maintaining a constant height of the idle charge should be solved by the level controller, and the task of fulfilling the $T_{iron} \to T_{iron\,max}$ criterion should be solved by controlling the air supply to the tuyere box.

3. 2. Construction of the optimal law for regulating the level of the height of the idle charge

The mathematical model describing the process of changing the upper level of the idle charge can be represented as follows:

$$F\frac{dh_{sh}}{dt} = Q_{c1} - Q_{c2}, \quad (5)$$

where F – the inside area of the cupola, Q_{c1} – the consumption of coke loaded into the cupola, Q_{c2} – the consumption of coke due to the combustion process.

An increase in Q_{c2} consumption causes a drop in the upper level of the idle charge from the initial height by $\Delta h = h_{sh} - h_{sh\,min} = \Delta h^{-}$. Such a change is perceived by the control system, which loads the necessary portion of the fuel charge, which compensates for the consumption of coke Q_{c2}.

If an electric motor acts as an actuating mechanism in the coke charge loading system and the speed of rotation of the electric motor shaft is proportional to the magnitude and sign of the applied voltage, the analytical dependence of the change in the consumption of coke loaded into the cupola has the form:

$$\frac{dQ_{c1}}{dt} = kU, \tag{6}$$

where k – an integral coefficient that takes into account the influence of the characteristics of a particular electric drive.

The mathematical model of the process can be represented by a system of two differential equations if to introduce the following notation:

$x_1 = \Delta Q_{c1}$ – change in the consumption of coke loaded into the cupola;

$x_2 = F\Delta h_{sh}$ – change in the volume of the fuel charge with an increase in Q_{c2} consumption;

$q = \Delta Q_{c2}$ – change in coke consumption due to the combustion process;

$u_1 = kU_1$ – control proportional to the voltage applied to the electric motor, and the voltage U is limited by the condition:

$$-U_{10} \le U_1 \le U_{10}. \tag{7}$$

$$\begin{cases} \dfrac{dx_1}{dt} = u_1, \\ \dfrac{dx_2}{dt} = x_1 - q. \end{cases} \tag{8}$$

The result of such a representation of the model is its reduction to a typical form [47] and the possibility of determining, based on the Pontryagin maximum principle, the optimal control (9), which transfers the system from the initial state $\left(x_1^{(0)}, x_2^{(0)}\right)$ to the final one along the phase trajectory (10):

$$u_{1opt} = u_{10}\,\mathrm{sgn}\left[\frac{1}{2u_0}\left(x_1 - q\right)^2 \mathrm{sgn}\left(q - x_1\right) - x_2\right], \tag{9}$$

where u_0 – the boundary value of the control;

$$x_2 = \frac{1}{2u_1}\left(x_1 - q\right)^2 + x_2^{(0)} - \frac{1}{2u_1}\left(x_1^{(0)} - q\right)^2. \tag{10}$$

The proposed procedure for obtaining the optimal law for regulating the level of the idle charge height, based on bringing the process model to a typical form and then applying the maximum principle, can be used to synthesize the optimal controller in the cupola charging system. In this case, the technical implementation may be part of an automated or automatic control system for the cupola melting process.

3. 3. Synthesis of optimal air flow control

The proposed procedure for the synthesis of optimal control of the air flow rate supplied to the tuyere box includes the following steps:

Stage 1. Construction of acceleration curves $Q = Q(t)$ for fixed values of damper rotation angle (φ) on the pipeline supplying air to the tuyere box.

Stage 2. Formation of the nomogram $Q = f_i(\varphi)$ on the basis of graphical-analytical plotting of dependencies $Q = f_i(\varphi)$ for each time $t = t_i$ in the selected range.

Stage 3. Calculation of the optimal air flow from equation (4) and applying this value to the nomogram $Q = f_i(\varphi)$.

The implementation of stages 1–3 is illustrated in **Fig. 3**:

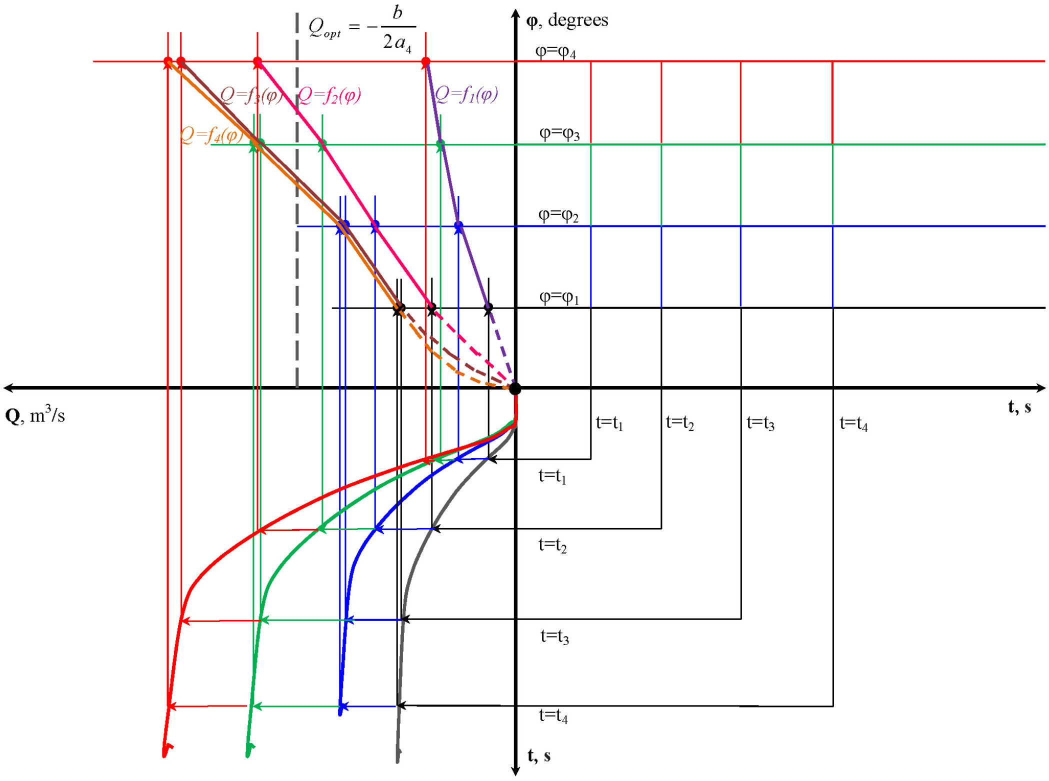

Fig. 3. The principle of constructing the nomogram $Q=f_i(\varphi)$: ––– – time moment $t=t_1$, ––– – time moment $t=t_2$, ––– – time moment $t=t_3$, ––– – time moment $t=t_4$; $Q=f_1(\varphi)$ – air flow curve as a function of damper position for $t=t_1$, $Q=f_2(\varphi)$ – air flow curve as a function of damper position for $t=t_2$, $Q=f_3(\varphi)$ – curve air flow rate as a function of damper position for time $t=t_3$, $Q=f_4(\varphi)$ – air flow curve as a function of damper position for time $t=t_4$

Stage 4. Adaptive mathematical modeling [48], using an adaptive algorithm [49], which allows determining the predictive value of Q by a given time step ahead. The time step value (Δt) corresponds to the time interval after which the lower level of the fuel charge reaches the upper level of the idle charge.

Stage 5. Construction of a mathematical model of the form $\Delta Q=\Delta Q(\varphi, \Delta t)$.

Stage 6. Calculation of the deviation of the actual air flow rate by a step forward in the time interval Δt from the optimal air flow rate calculated from equation (4): $\Delta Q=Q-Q_{opt}$, with the actual value of the damper rotation angle in this heat $\varphi=\varphi_i=\text{const}$.

Stage 7. Search for the optimal control of the damper position, which ensures the achievement of the optimal value of air flow Q_{opt} in the shortest possible time. The mathematical model of the control object has the form:

$$\frac{d\varphi}{dt}=u_2. \tag{11}$$

The task of finding the optimal control is to determine the optimal control $u_2(t)$ that takes the process from a given initial state $\varphi^{(0)}$ to the final state $\varphi^{(k)}$ in the minimum time if the range of possible values of the control action is subject to a constraint of the form:

$$-U_{20} \le u_2 \le U_{20}, \tag{12}$$

that is, the damper is assumed to be electrically actuated. The initial state corresponds to the angle of rotation of the damper, adopted in this melting ($\varphi=\varphi_i=\text{const}$).

The final state is determined from the following considerations. The mathematical model obtained at step 5 can be represented by a regression equation in which the output variable ΔQ is determined from the nomogram (**Fig. 3**) according to the plan of the full factorial experiment 2^2. The plan of the experiment is based on the factors φ and Δt, varied in the ranges $\varphi = [\varphi_{min}; \varphi_{max}]$ and $\Delta t = [\Delta t_{min}; \Delta t_{max}]$. If the adequacy is confirmed for the linear model, then the equation describing the difference in flow rates for two different moments in the time range $[\Delta t_{min}; \Delta t_{max}]$ and the range of damper position angles $[\varphi_{min}; \varphi_{max}]$, has the form:

$$\Delta Q = c_0 + c_1\varphi + c_2\Delta t. \tag{13}$$

Fixing the time interval Δt, after which the lower level of the fuel charge reaches the upper level of the idle charge, equation (13) takes the form:

$$\Delta Q = d_0 + c_1\varphi, \tag{14}$$

if to introduce the notation $d_0 = c_0 + c_2\Delta t$.

Knowing the predicted value of air flow Q per step ahead in time Δt, and based on the fact that the angle of rotation of the damper should ensure the fulfillment of the condition $Q = Q_{opt}$ at this point in time, the equation for determining the final state when searching for optimal control takes the form:

$$\varphi^{(k)} = \frac{Q - Q_{opt} - d_0}{c_1}, \tag{15}$$

where

$$Q_{opt} = -\frac{b}{2a_4}. \tag{16}$$

The optimal control determined on the basis of the Pontryagin maximum principle, based on the model (11) in the presence of constraint (12) with the initial condition $\varphi^{(0)} = \varphi_i = \text{const}$, and the final state (15) has the form:

$$u_{2opt} = U \operatorname{sgn}\left(\varphi^{(k)} - \varphi^{(0)}\right). \tag{17}$$

This control ensures the transfer of the system from the state φ_i to the state $\varphi^{(k)}$ along the phase trajectory:

$$\varphi = \left[U \operatorname{sgn}\left(\varphi^{(k)} - \varphi_i\right)\right]t + \varphi_i, \tag{18}$$

during

$$t^{(k)} = \frac{\left|\varphi^{(k)} - \varphi_i\right|}{U}. \tag{19}$$

The proposed procedure for the synthesis of optimal control of the air flow rate blown into the cupola, which includes 7 successive stages, makes it possible to control the temperature regime of cupola melting, ensuring the fulfillment of the $T_{iron} \rightarrow T_{iron\,max}$ criterion for the level of the idle charge height maintained by the level controller, respectively (9).

3. 4. Control of the temperature profile of the cupola

The proposed procedures for synthesizing the optimal control of the temperature regime of cupola melting are built relative to the iron temperature controlled on the chute when the melt is discharged from the forehearth. However, from a process control point of view, it is equally important to determine the temperature of the system inside the cupola. This is due to the fact that knowledge of the temperature profile of the cupola, which is the temperature distribution in the furnace over the horizons, would make it possible to simulate physical and chemical processes in different zones, including the height of the idle charge. The formation of the chemical composition of cast iron depends on these processes, therefore, knowledge of the temperature at the lower and upper levels of the idle charge can be used to simulate heat and mass transfer processes in the «coke-melt» system, which affect the degree of development of reduction-oxidation reactions in this zone.

If to use the iron temperature on the chute as an informative parameter when it is dispensed from the cupola, then the fact of changing the position of the upper level of the idle charge is determined from the following condition (**Fig. 1**):

$$\begin{aligned} &\text{IF } T_{iron}\big|_{t=t_i} < \left[T_{iron}\right] \text{ and } P\big|_{t=t_i} > \left[P\right] \text{ then } \Delta h = h_{sh} - h_{sh\,min} = \Delta h^{-}, \\ &\text{IF } T_{iron}\big|_{t=t_i} > \left[T_{iron}\right] \text{ and } P\big|_{t=t_i} < \left[P\right] \text{ then } \Delta h = h_{sh\,max} - h_{sh} = \Delta h^{+}, \end{aligned} \quad (20)$$

where $[T_{iron}]$ – the actual cast iron temperature determined for a given position of the upper level of the idle charge, $[P]$ – the actual productivity of the cupola, determined for a given position of the upper level of the idle charge, Δh – the deviation of the position of the upper level of the idle charge (**Fig. 1**).

Taking into account that the iron temperature depends on the temperature of the coke in the idle shell, condition (20) can be used to determine the position of the upper level of the idle shell based on temperature measurements in the working space of the cupola, in particular, by the height of the idle shell. In this case, the informative parameter about the actual position of the upper level of the empty charge is the temperature value at the horizon $h = h_{sh}$. The temperature deviation ΔT on this horizon (**Fig. 1**) indicates the need to load the fuel charge of the required volume. The corresponding condition looks like:

$$\text{IF } \Delta T\big|_{h \neq h_{sh}} \neq 0 \text{ and } P \neq \left[P\right] \text{ then } \Delta h \neq 0. \quad (21)$$

To implement condition (21), it is necessary to ensure the maximum accuracy of temperature measurements along the horizons of the cupola. For this, the measurement principle can be used, based on the arrangement of sensors according to D-optimal plans on the segment. Such plans make it possible to estimate the value of output variables with maximum accuracy by minimizing the determinant of the dispersion matrix [50].

The output variable is the temperature at the point of contact of the lining, coke and molten iron flowing through the pores between the pieces of coke ($T_{f\text{-}c\text{-}i}$). The principle of arranging sensors according to the points of the D-optimal plan is shown in **Fig. 4**:

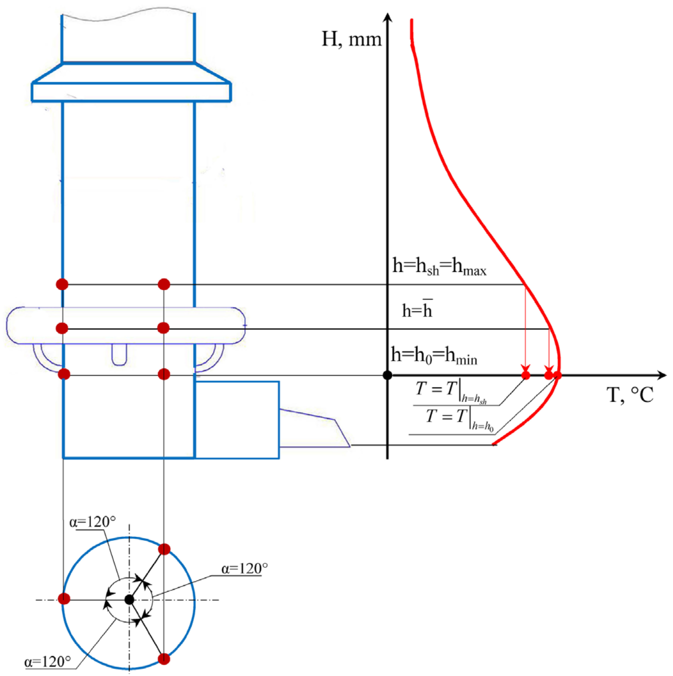

Fig. 4. The principle of arranging sensors according to the points of the D-optimal plan: ● – sensor installation point

It should be noted that the temperature profile is shown conditionally and reflects the temperature distribution of the gas phase as the main heat carrier in the cupola. However, taking into account the correlation between the temperature of the gas phase and the temperature in the idle charge, the profile in the latter will have a similar form. This means that in a given zone of the cupola, the temperature distribution along the height can be represented as a parabola, that is, it is enough to install sensors at three levels in height and at three points along the horizon corresponding to this level. In this case, the angle between the sensors is 120° (**Fig. 4**). Thus, the input variable for the implementation of the D-optimal plan in terms of height is the variable h, and for the implementation of the D-optimal plan for the internal contour of the cupola, the variable α. Both variables are reduced to the normalized form:

$$x_i = \frac{x_{in} - \bar{x}_i}{I_i}, \tag{22}$$

where x_i – the normalized values of the input variables, i – indices identifying the input variables: $i=1$ for h, $i=2$ for α, x_{in} – the natural values of the input variables, $\bar{x}_i$ – the average values of the input variables, I_i – the intervals of variation of the input variables:

$$I_i = x_{in}^{\max} - \bar{x}_i = \bar{x}_i - x_{in}^{\min}. \tag{23}$$

Operation (22) transforms the natural values of the input variables into the normalized range [–1; +1]. The construction of the D-optimal plan is carried out at the points of the normalized range:

– by height: $x_{1min}=-1$, $x_{1max}=+1$, $\bar{x}_1 = 0$,

– by angle: $x_{2min}=-1$, $x_{2max}=+1$, $\bar{x}_2 = 0$.

The equation describing the temperature profile along the height as a function of the normalized input variable has the form:

$$T_{f-c-i} = \beta_0 + \beta_1 x_1 + \beta_1 x_1^2, \tag{24}$$

where β_i – the coefficients to be determined.

In its natural form, equation (24) is represented as follows:

$$T_{f-c-i} = \beta_0 + \beta_1 \frac{x_1 - \bar{x}_1}{I_1} + \beta_1 \left(\frac{x_1 - \bar{x}_1}{I_1}\right)^2. \tag{25}$$

The equation describing the temperature profile along the inner contour of the cupola has a similar form.

Based on this structure of the equation:

– the matrix of the D-optimal design has the form:

$$\mathbf{F} = \begin{pmatrix} 1 & -1 & 1 \\ 1 & 0 & 0 \\ 1 & 1 & 1 \end{pmatrix},$$

– the transposed matrix of the D-optimal design has the form:

$$\mathbf{F^T} = \begin{pmatrix} 1 & 1 & 1 \\ -1 & 0 & 1 \\ 1 & 0 & 1 \end{pmatrix},$$

– the normalized dispersion matrix has the form:

$$\mathbf{D} = \begin{pmatrix} 3 & 0 & -3 \\ 0 & 1.5 & 0 \\ -3 & 0 & 4.5 \end{pmatrix}.$$

Estimates of the coefficients of equation (24) are calculated by the formula:

$$\mathbf{B}=\frac{1}{3}\mathbf{D}\mathbf{F}^{\mathrm{T}}\mathbf{Y}, \tag{26}$$

where **B** – matrix of coefficient estimates, **Y** – column vector of values of the output variable ($T_{f\text{-}c\text{-}i}$).

The variance of the estimate of the output variable is determined by the formula:

$$s^2_{T_{f-c-i}}(x)=\mathbf{f}^{\mathrm{T}}(\mathbf{x})\left(\mathbf{F}^{\mathrm{T}}\mathbf{F}\right)^{-1}\mathbf{f}(\mathbf{x})s^2, \tag{27}$$

where $\mathbf{f}(\mathbf{x})=\begin{pmatrix}1\\ x_i\\ x_i^2\end{pmatrix}$, $\mathbf{f}^{\mathrm{T}}(\mathbf{x})=\begin{pmatrix}1 & x_i & x_i^2\end{pmatrix}$, s^2 – variance estimate:

$$s^2=\frac{1}{(n\nu-n)}\sum_{j=1}^{n}\left(\left(T^{calc}_{f-c-i}\right)_j-\left(T^{ex}_{f-c-i}\right)_j\right)^2, \tag{28}$$

where $n=3$ – the number of points of the D-optimal plan, ν – the number of parallel measurements at each point of the D-optimal plan, T^{calc}_{f-c-i} – the value of the output variable calculated by equation (24), T^{ex}_{f-c-i} – the experimental value of the output variable taken from the sensors.

The resulting equation (24) makes it possible to calculate the temperature in the «lining – coke – melt» system at the sensor installation point with maximum accuracy. The estimate of the temperature determination variance in this case is determined from (28).

3. 5. Limitations and directions of research development

The proposed experimental-industrial method for synthesizing the optimal temperature control of cupola melting is limited at the level of procedures that completely form the architecture of the method:

– procedures for obtaining the optimal law for regulating the level of the height of the idle charge;

– procedures for the synthesis of optimal control of the air flow rate supplied to the tuyere box;

– the principle of temperature control along the horizons and the periphery of the working space of the cupola.

The conceptual solution for the synthesis of optimal temperature control is based on the fact that the height of the idle charge is known and must be maintained constant, and the achievement of the maximum temperature is ensured only by air consumption. However, the height of the idle charge is also an optimized technological factor. Therefore, the mathematical model (1) should be investigated for the presence of an optimum, determined by the best values of both input variables – both the volume of coke of the idle charge and the air flow. Given the presence of restrictions imposed on the input variables, not one optimal solution can be obtained, but a set of suboptimal solutions. Each of them is located at the intersection of the response surface (1) constructed in the normed space of input variables and the surface describing the constraints. The principle of constructing such solutions can be found, for example, in [51, 52]. Constraints look like a cylinder with a radius at the base $r=\sqrt{V_c^2+Q^2}$, where the values of the input variables are taken in a normalized form from the interval [–1; +1], moreover, the upper range for the variable V_c is limited by the geometric dimensions of the cupola, and for the variable Q, it is limited by the capabilities of the equipment complex that pumps air into the tuyere box. At the same time, many other factors related to the calorific value of coke, its chemical composition, fraction and method of coke stacking, and aerodynamic conditions in the working space of the cupola have a limiting effect. Some of these factors cannot be accurately determined, therefore, even with the maximum possible fan performance, the significance of the effect of air flow on temperature increase in the system may turn out to be negligible.

It should also be noted that the study is limited to two input variables, and their number can be increased by including two more known factors of intensification of the cupola process into consideration – enrichment of the injected air with oxygen and the degree of air heating.

An increase in the number of control factors would make it possible to obtain better results, both in terms of increasing the temperature of the cast iron, and in terms of the possibilities of controlling the melting process.

The practical use of the proposed principle of temperature control based on the arrangement of sensors according to the D-optimal plan should imply the possibility of long-term operation of a set of control and measuring equipment. Given the aggressive conditions of a controlled environment, this task becomes difficult and costly, and its solution must be justified by the benefits derived from the final result. Such benefits should consist in obtaining high-quality pig iron or minimizing the cost of finishing it in the secondary smelter in the case of using the duplex process. The resulting cast iron must meet the specified requirements for chemical composition and properties.

The development of the proposed method, taking into account the above limitations, should be focused on improving the control process of cupola melting with the possibility of technical implementation of a control system that provides for several modes: manual, automated, automatic.

4. Conclusions

The proposed conceptual solution for the synthesis of optimal temperature control allows the use of two levels of control: the task of maintaining a constant height of the idle charge should be solved by the level controller, and the problem of increasing the temperature of cast iron should be solved by controlling the air supply to the tuyere box. A feature of such solutions is that the search for optimal control is preceded by obtaining a mathematical model in the form of a regression equation that describes the effect of coke volume and air flow on iron temperature. The analysis of such a model involves determining the optimal flow rate of air supplied to the tuyere box, according to the criterion of the maximum temperature of cast iron at an adjustable upper level of the idle charge.

It is shown that the problem of regulating the upper level of an idle charge can be solved by reducing the model of the regulation process to a typical form, followed by the use of the Pontryagin maximum principle.

The proposed procedure for synthesizing the optimal control of the air flow supplied to the tuyere box includes 7 successive stages, thanks to which it becomes possible to synthesize the optimal process control based on experimental and industrial studies that precede the search for optimal control.

The use of D-optimal plans for choosing the points of installation of the sensors makes it possible to determine the temperature profile of the cupola with maximum accuracy along its horizons and the periphery of the working space of the cupola. This makes it possible to indirectly determine the actual position of the upper level of the idle charge in order to implement the process of regulating the loading of the fuel charge and subsequent control of the air supply system entering the tuyere box.

Conflicts of interest

The author declares that he has no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

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Data availability

Data will be made available on reasonable request.

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