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OPTIMIZATION OF TECHNOLOGICAL MODES OF CUPOLA MELTING ACCORDING TO THE CRITERION OF MAXIMUM COMBUSTION TEMPERATURE

The object of research is the combustion temperature in the cupola furnace. The problem under study was the complexity of predicting the temperature as a function of the control parameters of the melting.

In the study, the control parameters were selected as the temperature of the air heating blown into the tuyeres and the completeness of fuel combustion. Using orthogonal experimental planning, a mathematical model was constructed in the form of a second-order polynomial, which allowed to identify the patterns of influence of each control factor on the resulting value – the combustion temperature.

The resulting mathematical model allowed to find out that both input variables are significant. However, if the nature of the influence of the air heating temperature on the combustion temperature is linear, then the completeness of combustion affects nonlinearly. The accuracy of the model turned out to be satisfactory, because all experimental data fell within the confidence intervals with a confidence probability of $P=0.99$. This allows to state the possibility of using the constructed model to predict the combustion temperature within the planning area.

The ridge analysis of the response surface established that the theoretical maximum value of the combustion temperature at the boundary of the planning area is about 3000°C. This corresponds to the values of the input variables $T_{air}\approx 1120$°C and $\eta_0 \approx 82$%. However, due to the fact that ensuring the air heating temperature at the level of 1120°C may encounter technical complexity of implementation, the following values of the input variables can be recommended: $T_{air}=783$–1060°C, $\eta_0=71$–80. They provide combustion temperatures in the range of 2690–2980°C, i. e. values close to the suboptimal one determined by the ridge analysis.

These data allow making adjustments to the melting process, including being used for further searching for optimal melting control. The obtained solutions can be used in iron foundry shops of industrial enterprises equipped with cupola furnaces.

Keywords: *cupola melting, cupola combustion temperature, air heating temperature, completeness of fuel combustion.*

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1. Introduction

Despite the fact that cupola furnaces can be attributed to the oldest melting furnaces, their research continues to this day [1–3], despite a significant drawback in terms of environmental impact [4]. Ways to eliminate this drawback are to create new furnace designs or improve them in a way that takes into account preventive measures to reduce the negative impact on the environment [5, 6]. However, it should be borne in mind that the volume and composition of emissions from the cupola furnace are side factors, while the main purpose of cupola furnaces is to obtain high-quality cast iron in the required quantity. Therefore, for example, in work [7] the importance of complex solutions is emphasized, in particular through the combination of technological flows to regulate the composition and temperature of cast iron. In works [8, 9] the importance of intensification of cupola melting is determined, and in work [10] the importance of adequate technological description. Appropriate complex solutions can make it possible to increase melting performance while simultaneously achieving the effect of environmental safety [11].

Modern approaches to improving the cupola process are focused primarily on solving automation issues, in particular on the development and implementation of technical means that remove uncertainty in the assessment of current melting parameters [12]. A suitable example may be solutions for the development of controllers or algorithms and hardware systems for assessing the reliability of sensor readings [13]. However, the development and implementation of such means must take into account the fact that uncertainty regarding the values of process parameters requires not a deterministic, but a fuzzy description of the process. Accordingly, fuzzy control, in particular, of the melting temperature regime [14], must be implemented. In this context, it is also important to consider the possibilities of rational heat utilization [15].

All this confirms that the multifactorial nature of the process is the main circumstance in the issue of controlling the cupola process. Complex solutions, if rational, can contribute to increasing melting parameters, in particular the chemical composition, properties and temperature of cast iron, which are components of the quality of finished castings [16, 17]. Among the factors of such complex solutions can be noted rational dosing of charge and coke [18] and the volume of air supplied to the tuyeres [19]. Considering these factors as components of real-time process control, it is advisable to use adaptive modeling algorithms [20, 21] and the synthesis of optimal regulation of the temperature regime and the melt delivery process based on the typification of the mathematical description of the control object [22]. The latter is cupola melting, for which the control functionality should be selected as speed in the context of ensuring the specified melt temperature, its quantity and quality according to the chemical composition of the melt. The systematization of control factors was done in the study [23], which presents possible relationships between input and output process variables. In the context of the complexity of cupola control due to the uncertainty of many process parameters and the uncontrollability of many of them, new ideas are important regarding the indirect determination of cupola melting parameters. Among them, one can mention the determination of the temperature regime of cupola melting by slag viscosity [24], as a development of the idea of identifying the temperature regime of cast iron melting in induction furnaces [25, 26].

It is also necessary to note the importance of engineering solutions aimed at implementing scientific results regarding factors influencing the cupola process. Examples include devices for introducing fuel and post-regeneration dust through tuyeres [27] or solutions of a design and technological nature [28].

Thus, the results of existing research are aimed at obtaining solutions that can increase the efficiency of cupola melting processes and minimize the negative impact on the environment of the cupola melting process. This confirms the relevance of the topic, because the modern level of development of technologies and society requires complex approaches to the development or improvement of technological processes. The corresponding solutions are relevant for practice, because they can also be used to develop modern control and automation systems, without which it is difficult to withstand competition. The latter is based on obtaining high-quality products in a given quantity while minimizing production costs and environmental damage.

Generalizing the results of the analysis of the current state of the issues related to cupola melting allows to draw the following conclusion. The main problem associated with the search for ways to obtain complex solutions is associated with the multifactorial nature of the process and the difficulties of controlling the melting parameters. The elimination of relevant problematic issues is possible by obtaining adequate mathematical models that describe the cupola melting process, either according to the black box principle [29], or based on studies of physicochemical processes occurring in the working space of the furnace [30]. The obtained solutions can also be considered in the context of building intelligent control of cupola furnaces [31].

Thus, *the aim of research* is to build a mathematical model that would allow determining the optimal technological modes of cupola melting using the criterion of the maximum combustion temperature, as one of the main indicators of the efficiency of the process.

2. Materials and Methods

The object of research is the combustion temperature in the cupola furnace. The subject of research is to determine the patterns of influence of the heating temperature of the air supplied to the tuyeres and the completeness of combustion on the temperature of the cast iron. The input data were the results of practical data given in [23].

In Table 1, the following notations are adopted: $T_{combustion}$ – combustion temperature, T_{air} – temperature of air blown into the tuyeres, η_0 – completeness of coke combustion.

A second-order orthogonal design was chosen, the implementation of which can be used to construct a mathematical model in the form of a second-degree polynomial with its general representation [32]

$$y = a_0 + 2\mathbf{a}^{\mathrm{T}}\mathbf{x} + \mathbf{x}^{\mathrm{T}}\mathbf{A}\mathbf{x}, \quad (1)$$

where y – the combustion temperature ($T_{combustion}$, °C), $\mathbf{x}$ – the matrix of influence factors (input variables) with components x_1 and x_2: x_1 – the influence factor Tair, °C, x_2 – the influence factor η_0, %, in normalized form, $\mathbf{x}^{\mathrm{T}}$ – the transposed matrix of influence factors, $\mathbf{a}^{\mathrm{T}}$ – the transposed matrix of linear members of the model, $\mathbf{A}$ – the matrix of nonlinear members of the model.

$$a_i = c_1 \sum_{j=1}^{N} x^j y^j,\ i = 1, \ldots, n, \quad (2)$$

$$a_i = c_2 \left[(x_{i-n}^j)^2 - \beta \right] y^j,\ i = n+1, \ldots, 2n, \quad (3)$$

$$a_i = c_3 \sum_{j=1}^{N} x_\mu^j x_\lambda^j y^j,\ i = 1, \ldots, n,\ \mu \neq \lambda,\ i = 2n+1, \ldots, k, \quad (4)$$

$$a_0 = \frac{1}{N} \sum_{j=1}^{N} y^j - \beta \sum_{j=1}^{N} a_{n+i}, \quad (5)$$

where c_1, c_2, c_3 – the coefficients for linear, quadratic and pairwise relationships, respectively, n – the number of linear terms in the equation ($n=2$), N – the number of experiments ($N=9$), Table 2, [33], β – a parameter calculated by the formula

$$\beta = \frac{\sum_{j=1}^{N} (x_i^j)^2}{N} = \frac{2^{n-p} + \alpha}{N}, \quad (6)$$

where α – the shoulder of the star points.

Table 1

Data for constructing the dependence $T_{combustion} = f(T_{air}, \eta_0)$ [23]

Experiment No.	Melting process parameters		$T_{combustion}$, °C
	T_{air}, °C	$\eta_0 = \frac{CO_2}{CO_2 + CO} 100\%$	
1	200	20	1700
2	200	60	2100
3	200	100	2250
4	600	20	2100
5	600	60	2450
6	600	100	2600
7	1000	20	2400
8	1000	60	2800
9	1000	100	3000

Table 2

Selected parameters of the central orthogonal design

Design core	N	α	β	Coefficients for linear, quadratic and pairwise relationships, from which estimates of variances of the coefficients of the mathematical model are calculated (1)			
				c_0	c_1	c_2	c_3
2^2	9	1	0.6667	0.1111	0.1667	0.5	0.25

The formula was used to estimate the variances of the coefficients of the mathematical model

$$s_i^2 = \begin{cases} s^2 c_0,\ i = 0, \\ s^2 c_1,\ i = 1, \ldots, n, \\ s^2 c_2,\ i = n+1, \ldots, 2n, \\ s^2 c_3,\ i = 2n+1, \ldots, k, \end{cases} \quad (7)$$

where s^2 – the estimate of the variance of the inadequacy of the model (1).

The response surface was studied based on the methods described in [34, 35]. In this case, the parametric description had the form

$$\begin{cases} \mathbf{x}^*(\lambda)=(\lambda\mathbf{I}-\mathbf{A})^{-1}\mathbf{a}, \\ r^*(\lambda)=\sqrt{\mathbf{x}^{*\mathrm{T}}\mathbf{x}^*}, \\ y^*(\lambda)=\mathbf{a_0}+2\mathbf{a}^{\mathrm{T}}\mathbf{x}^*+\mathbf{x}^{*\mathrm{T}}\mathbf{A}\mathbf{x}^*, \end{cases} \tag{8}$$

where $\mathbf{x}^*(\lambda)$ – the matrix of suboptimal values of the input variables in the normalized form, depending on the parameter λ, $\mathbf{x}^{*\mathrm{T}}(\lambda)$ – the transposed matrix of suboptimal values of the input variables, $r^*(\lambda)$ – the radius of the circle bounding the domain of the input variables, $\mathbf{I}$ – the identity matrix, $\mathbf{a}^{\mathrm{T}}$ – the transposed matrix of the coefficient estimates for linear terms.

The normalization of input variables was carried out according to the formula

$$x_i=\frac{x_{in}-\overline{x}_i}{I_i}, \tag{9}$$

where x_i – the normalized values of input variables, i – indices of input variables: $i=1$ for T_{air}, $i=2$ for q_{coke}, x_{in} – the natural values of input variables, $\overline{x}_i$ – average values of input variables, I_i – the intervals of variation of input variables

$$I_i=x_{in}^{\max}-\overline{x}_i=\overline{x}_i-x_{in}^{\min}. \tag{10}$$

Operation (10) converts the natural values of input variables into the normalized range [– 1; + 1]. The inverse transformation allows to determine the mathematical model in its natural form by recalculating the values of the coefficients.

The accuracy of the model was determined by comparing experimental data (Table 1) and calculating the temperatures of cast iron and was assessed by the experimental values falling into the confidence interval for a confidence probability of 99% and a significance level of 0.01.

3. Results and Discussion

Table 3 shows the results of calculating the parameters of the model (1), and Fig. 1 shows the results of assessing its accuracy.

Table 3

Parameters of the mathematical model (1)

a_0	a	A
2456	$\begin{pmatrix}179.2\\137.53\end{pmatrix}$	$\begin{pmatrix}0 & 0\\0 & -108.69\end{pmatrix}$

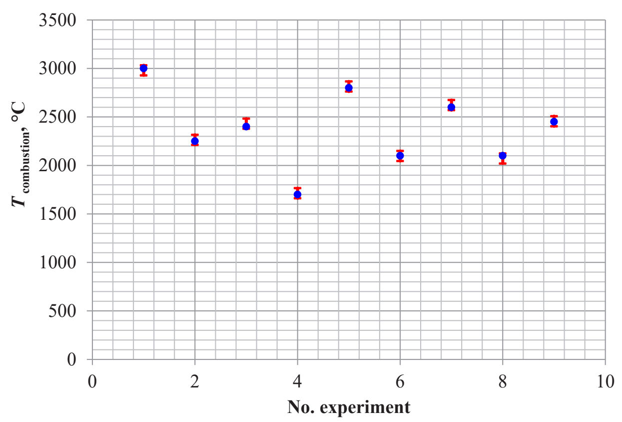

Fig. 1. Results of the accuracy assessment of the mathematical model $T_{combustion}=f(T_{air}, \eta_0)$: blue dots – experimental data, red ranges – confidence interval

As can be seen from Fig. 1, all experimental data fell within the confidence intervals, which allows to speak about the accuracy of the model in the selected planning area.

The general appearance of the response surface is shown in Fig. 2.

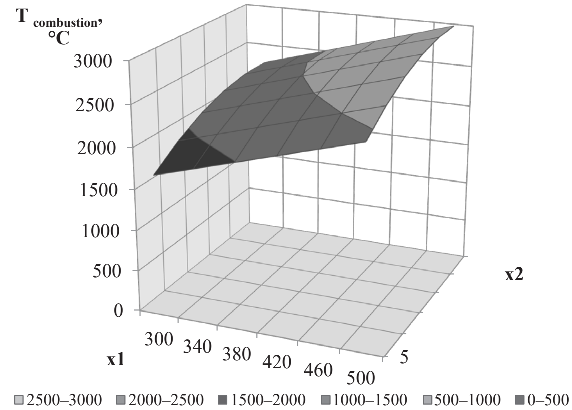

Fig. 2. Response surface $T_{combustion}=f(T_{air}, \eta_0)$, presented in normalized values of input variables

As follows from the coefficients of the obtained model (Table 3) and the nature of the response surface (Fig. 2), the significance of the air heating temperature in terms of the impact on the combustion temperature is greater than the significance of the impact of the combustion completeness. However, if the nature of the impact of the air heating temperature is linear, then the completeness of combustion affects nonlinearly. It is important that it is impossible to achieve the optimum combustion temperature within the experimental design and it is only possible to talk about certain suboptimal solutions based on a parametric description in the form of (8). Fig. 3–5 show the corresponding results in the form of parametric descriptions of the form $r^*=r^*(\lambda)$, $y^*=y^*(\lambda)$, $y^*=y^*(r^*)$.

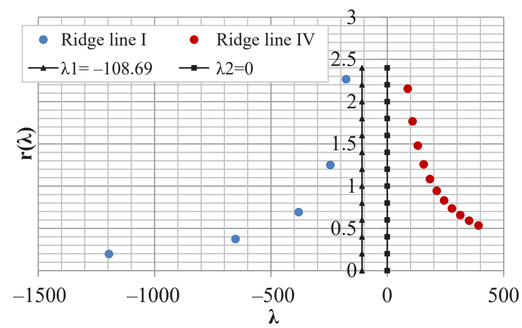

Fig. 3. Parametric description $r^*=r^*(\lambda)$

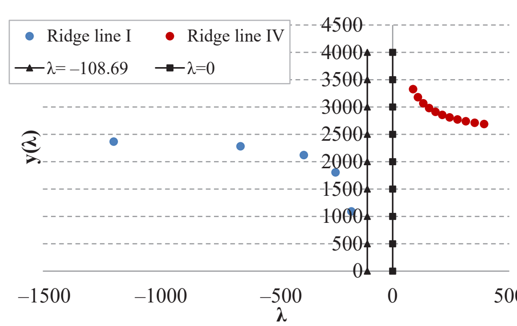

Fig. 4. Parametric description $y^*=y^*(\lambda)$

From Fig. 5 it is seen that the theoretical maximum value of the combustion temperature at the boundary of the planning area $r=1.414$ is reached on the ridge line IV and is about 3000°C. This corresponds to the values of the input variables $T_{air}\approx 1120°C$ and $\eta_0\approx 82\%$. However, ensuring the air heating temperature at the level of 1120°C may encounter technical complexity of implementation, so it is necessary to look for close solutions. By proximity let's mean such values of T_{air} and η_0 that provide close to suboptimal values of the combustion temperature. For this purpose, the dependence $x_2^*=x_2^*(x_1^*)$ can be constructed (Fig. 6).

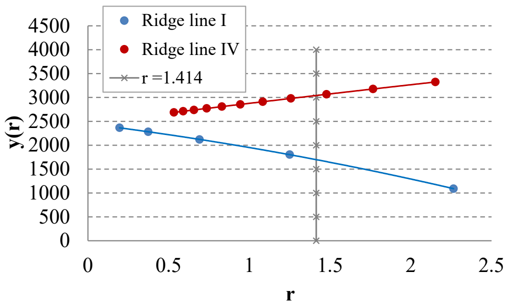

Fig. 5. Parametric description $y^*=y^*(r^*)$

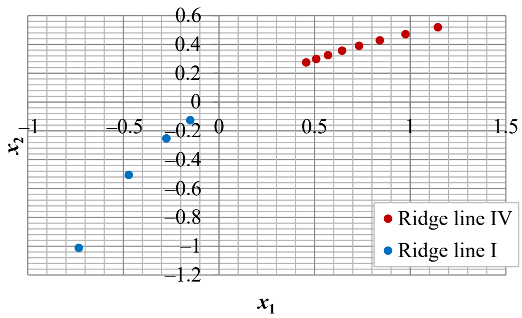

Fig. 6. Dependence $x_2^*=x_2^*(x_1^*)$ for determining T_{air} and η_0 in normalized form, providing close to suboptimal values of combustion temperature

Special attention should be paid to the dependence for ridge line IV. The corresponding ratios of the values of the input variables provide combustion temperatures in the range of 2690–2980°C. In comparison, the ratios of the values of the input variables characteristic of ridge line I provide a temperature range only at the level of about 1800–2370°C. At the same time, the actual values of the input variables, calculated according to formula (9), are for ridge line IV: $T_{air}=783–1060°C$, $\eta_0=71–80$. These ranges of values can be chosen as recommended.

The limitations of research are related to the ranges of variation of the input variables. However, it is important to note that the results obtained should be treated with some caution, because they were obtained from generalized data from the point of view of constructive and technological solutions for cupola furnaces. This is the drawback of research. Nevertheless, the presence of such solutions can be useful, because it is of interest to link the combustion temperature with the temperature in the working space of the furnace along the horizons of the cupola furnace. This would make it possible to determine the mechanisms of the processes occurring in the furnace and build other models, in particular thermodynamic and kinetic. This, in turn, can open up opportunities for a rational and justified choice of fuel [36], on which the physicochemical processes developing in the working space of the furnace depend. Thus, a complete model representation of cupola melting can be formed for the search and implementation of optimal control of cupola melting. Thus, this is what can become the subject of further research.

4. Conclusions

The obtained mathematical model, which describes the regularities of the influence of the temperature of the air blown into the tuyeres and the completeness of combustion on the combustion temperature, made it possible to find out that both input variables are significant. However, if the nature of the influence of the air heating temperature on the combustion temperature is linear, then the completeness of combustion affects nonlinearly.

The accuracy of the model turned out to be satisfactory, because all experimental data fell within the confidence intervals with a confidence probability of $P=0.99$. This allows to state the possibility of using the constructed model to predict the combustion temperature within the planning area.

By ridge analysis of the response surface, it was established that the theoretical maximum value of the combustion temperature at the boundary of the planning area is about 3000°C. This corresponds to the values of the input variables $T_{air}\approx 1120°C$ and $\eta_0\approx 82\%$. However, since ensuring the air heating temperature at 1120°C may encounter technical difficulties in implementation, the following values of input variables can be recommended: $T_{air}=783–1060°C$, $\eta_0=71–80$. They provide combustion temperatures in the range of 2690–2980°C, i. e. values close to the suboptimal one determined by the ridge analysis.

Conflict of interest

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

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Data availability

The manuscript has no associated data.

Use of artificial intelligence

The author used artificial intelligence technologies within permissible limits to provide their own verified data, as described in the research methodology section.

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