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Denys Nikolaiev,
Vadym Selivorstov,
Yuriy Dotsenko,
Oleksandr Dzevochko,
Alevtyna Pereverzieva,
Alona Dzevochko

IDENTIFICATION OF TEMPERATURE IN CUPOLA FURNACE BASED ON THE CONSTRUCTION OF THE "SLAG COMPOSITION – SLAG VISCOSITY" MODEL

The object of the study in the work is the temperature regime of melting in a cupola.

The existing problem is that due to the aggressive high-temperature environment, continuous measurement of the parameters of the internal environment in the working space of the cupola furnace is too difficult. Even with the implementation of such a possibility, errors of the first and second types may occur. This necessitates indirect control of the temperature regime, which could provide a solution to the identification problem – whether the control system is really operating in normal mode and meets the accuracy requirements, or whether there is a parametric failure along the corresponding control circuit.

The existence of the specified problem requires solutions related to the definition of criteria for evaluating the temperature regime, by which it would be possible to verify the reliable functioning of the melting control system.

A criterion for evaluating the temperature regime of melting by the viscosity of the slag as a function of its composition is proposed, which allows identifying the temperature regime of melting with an accuracy of 96 %. This result is due to the proposed two-stage procedure, in which the first stage is the construction of mathematical models that describe the influence of the slag composition on the viscosity, and the second is the construction of a criterion based on the density distribution of the discriminant function for both temperature regimes. Using the obtained criterion also makes it possible to determine the areas of chemical compositions, by which the temperature regime can also be identified. The relationships between the variables for the identification procedure are presented in the form of a structural diagram. The proposed solutions will allow determining the quality of the functioning of the temperature control loop in the melting control system based on periodic control.

The presented study will be useful for machine-building enterprises that have foundries in their structure, where cast iron is smelted for the manufacture of castings.

Keywords: *cupola melting, slag composition, temperature regime in the cupola furnace, slag viscosity, temperature control loop in the cupola furnace.*

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1. Introduction

Modern world trends require an increase in the rate of iron melting for mechanical engineering. Therefore, iron melting in cupola furnaces does not just remain the main process, but almost the only process that can ensure high productivity and obtain significant production volumes even in continuous mode. Because of this, the intensification of cupola melting should be considered an important trend, even despite the known and obvious disadvantages of this process: negative environmental impact, the difficulty of obtaining sufficiently high temperatures and stability of the chemical composition of cast iron. Unlike electric melting, for which optimal control systems [1, 2] and computer-integrated process control solutions [3, 4] can be implemented, cupola melting is characterized by complexity. This primarily concerns process control and sometimes even the impossibility of measuring important melting parameters. Under such conditions, the significant disadvantages of cupola melting should be eliminated by searching not only for effective technological solutions, but also by improving the automation of the melting process and searching for rational control options. Thus, in [5], a melting control algorithm based on determining the temperature profile and kinetics of carbon in the melt is proposed, and in [6], control is proposed at two levels: by regulating the charge and coke loading and the flow rate of blown air. However, the proposed solutions are mainly theoretical in nature, which requires additional engineering developments for practical implementation. Trends in improving the cupola process are presented in [7], where a description of the device for introducing fuel and post-regeneration dust through lances can be found. Among the measures to intensify melting aimed at improving the cupola process, in [8] a set of measures aimed at both the design and process technology is proposed. The issues of the influence of thermodynamic processes on increasing melting performance are considered in [9, 10], which investigate the problems of physico-chemical and thermal transformations during the interaction of various components in the cupola. However, it is important to note that in order to determine the possibility of process control based on the detection of thermodynamic or kinetic patterns, it is worth considering that cupola melting is characterized by a certain periodicity of changes in the initial conditions, on which the nature of the processes in the furnace depends. This is manifested in the periodicity of loading and instability of the composition of the charge. Therefore, it is necessary to take into account the drift factor of the process parameters [11], and accordingly adapt the control to this according to the principle of analogy with adaptive control of electric arc melting [12].

Heat utilization and use of heated air, as well as the utilization of dust emitted from the furnace, the products of which can also be directed for secondary use for the intensification of melting, are considered in the works [13, 14]. However, the solutions given in these works consider only individual technological and design factors as options for intensification of cupola melting. In contrast, in works [15–17], solutions aimed at automating melting are proposed – a software package for controlling the melting process is proposed [15], as well as options for arranging technical means and the structure of the cupola melting control system [16, 17]. However, the proposed solutions do not eliminate the problem of the complexity or impossibility of direct control of some melting parameters, for example, the temperature regime. To solve this problem, it is necessary to have mathematical models of the process that would provide the possibility of indirect measurement of melting parameters, the main ones of which are given in work [18]. The final melting parameters by which its possibility can be assessed are the temperature and chemical composition of cast iron, on which the mechanical characteristics depend, including the quality of finished castings [19]. The object of research is the temperature regime of melting in a cupola, a simplified functional diagram of which is given in Fig. 1 [5].

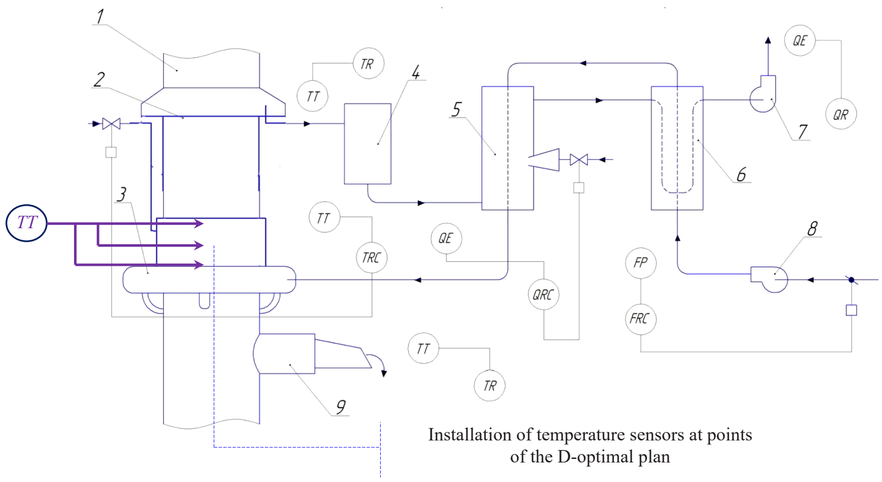

Fig. 1. Simplified functional diagram of the process and controlled parameters, including the locations of temperature sensors according to the points of the D-optimal plan [6]: 1 – cupola furnace; 2 – spark arrester; 3 – tuyeres; 4 – wet scrubber; 5 – radiation recuperator; 6 – convective recuperator; 7 – smoke exhauster; 8 – fan; 9 – slag collector

The main parameters of the melting process that must be controlled in the process are:
- temperature;
- pressure and gas composition;
- iron temperature;
- air flow rate and its heating temperature;
- oxygen content in the blast and combustion zone;
- water flow rate for the cooling system and the temperature at its inlet and outlet, coke and metal charge flow rate;
- sequence of loading with components.

The problematic part is that due to the aggressive high-temperature environment, continuous measurement of internal environment parameters in the working space is too difficult, in particular, this applies to temperature. In this case, even with the implementation of such a possibility, errors of the first and second types may occur. This necessitates indirect control of the temperature regime, which could provide a solution to the problem of identifying whether the control system is actually operating in normal mode and meets the accuracy requirements, or whether a parametric failure occurs along the corresponding control circuit.

The aim of research is to develop a criterion for assessing the temperature regime of the melt, which could provide acceptable accuracy in determining the compliance of the temperature regime of the melt with the given one.

2. Materials and Methods

The research methodology was based on the idea that the composition of the slag can be an informative parameter for determining the temperature regime of the melt, set out in [20] and developed in [21, 22], but relative to induction melting. Accordingly, the hypothesis of this study was that, by analogy with induction melting, an informative criterion for assessing the temperature regime can be determined based on the analysis of cupola slag. It was assumed that the factors that determine the acidity of the slags affect the viscosity of the slags with certain regularities, and the latter can be an informative parameter for identifying the temperature regime of the melt. Identification of the temperature regime by viscosity in the presence of mathematical models that relate the acidity of slags to viscosity will allow determining the areas of slag compositions, which will, in turn, determine the temperature regime.

Identification of the temperature regime is very important for the following reasons. Even if the temperature sensors are installed in accordance with the points of the D-optimal plan, which should guarantee the maximum assessment of the temperature and the position of the temperature maximum, as indicated in work [6], periodic monitoring is necessary to prevent failures in the temperature control circuit.

The initial data for the study were selected from work [18], from which anomalous values of the content of slag components were removed for two temperature regimes: regime No. 1 – $T=1400$ °C, regime No. 2 – $T=1500$ °C and converted into values of factors that determine the acidity of slags.

The initial data are given in Table 1.

At the first stage, mathematical models of the form were built:

$$y_{1,2}=a_0+a_1x_1+a_2x_2+a_3x_3+ \\ +a_4x_{12}+a_5x_{22}+a_6x_{32}+ \\ +a_7x_1x_2+a_8x_1x_3+a_9x_2x_3, \quad (1)$$

where $y_{1,2}$ – slag viscosity at a temperature of $T=1400$ °C (index 1), and at a temperature of $T=1500$ °C (index 2), Pa·s; x_1 – CaO/SiO$_2$ ratio; x_2 – MgO/Al$_2$O$_3$ ratio; x_3 – (CaO+MgO)/(SiO$_2$+Al$_2$O$_3$) ratio.

The intervals of variation of the input variables: $x_1=(0.25;\ 1.167)$, $x_2=(0.333;\ 1.714)$, $x_3=(0.36;\ 1)$.

The calculation of the coefficients of the models (1) was performed by the least squares method. The predictive capabilities of the models were checked based on the construction of confidence intervals and the inclusion of experimental viscosity values for both melting modes in them.

At the second stage, a rule for mode identification was built based on the simplification of the algorithm given in [20], reducing it to a one-dimensional representation. The accuracy of the identification was checked by the number of correctly determined temperature modes.

Table 1

Initial data of the study

No.	Slag composition, %			Slag viscosity, μ, Pa·s, at temperature	
	CaO/SiO_2	MgO/Al_2O_3	$(CaO+MgO)/(SiO_2+Al_2O_3)$	No. 1	No. 2
				T=1400 °C	T=1500 °C
1	0.5	0.5	0.5	7.2	3
2	0.556	0.333	0.5	2.8	0.8
3	0.875	1.714	1	4.5	1
4	1	1	1	4.8	2
5	1.167	0.706	1	6.5	2
6	1.05	0.714	1	6	2
7	1.05	0.714	1	5.6	2
8	0.25	1	0.36	8	2.5
9	0.333	0.5	0.36	7	0.8
10	0.452	0.853	0.52	2.2	0.7
11	0.371	0.867	0.45	7	2.2
12	0.291	0.714	0.38	6	1.8
13	0.267	1.111	0.38	6.7	1.7

3. Results and Discussion

The following mathematical models of viscosity in normalized form were obtained:

$$y_1 = 8.286 - 7.772x_1 + 17.122x_2 + 13.256x_3 - 189.491x_1^2 + \\ + 18.314x_2^2 - 157.331x_3^2 + 12.16x_1x_2 + 351.194x_1x_3 + 4.47x_2x_3, \quad (2)$$

$$y_2 = 1.564 - 10.532x_1 + 3.781x_2 + 14.179x_3 - 74.604x_1^2 + \\ + 8.478x_2^2 - 72.275x_3^2 + 8.631x_1x_2 + 150.884x_1x_3 + 7.189x_2x_3. \quad (3)$$

Table 2 presents the results of testing the predictive capabilities of models.

Table 2

Testing the predictive capabilities of models for determining temperature regimes

No.	Temperature regime					
	No. 1			No. 2		
	Experiment	Confidence interval limits		Experiment	Confidence interval limits	
	y_{1exp}	y_1^-	y_1^+	y_{2exp}	y_2^-	y_2^+
1	7.2	4.679	7.859	3	1.8	3.26
2	2.8	1.53	4.71	0.8	0.24	1.7
3	4.5	2.786	5.966	1	0.21	1.67
4	4.8	3.481	6.661	2	1.41	2.87
5	6.5	4.906	8.086	2	1.27	2.73
6	6	4.123	7.303	2	1.23	2.69
7	5.6	4.123	7.303	2	1.23	2.69
8	8	5.285	8.465	2.5	1.12	2.58
9	7	5.822	9.002	0.8	0.25	1.71
10	2.2	2.237	5.417	0.7	0.64	2.1
11	7	3.285	6.465	2.2	0.6	2.06
12	6	5.059	8.239	1.8	1.42	2.88
13	6.7	6.316	9.496	1.7	1.6	3.06

From Table 2 it is seen that both models demonstrate high predictive capabilities, because only one experimental value No. 11 fell outside the confidence interval. Therefore, the model data can be used to calculate the viscosity with the subsequent solution of the problem of identifying the temperature regime.

Fig. 2 shows the algorithm for identifying the temperature regime, and Fig. 3 shows the histograms of the distribution of the probability density values of the discriminant function.

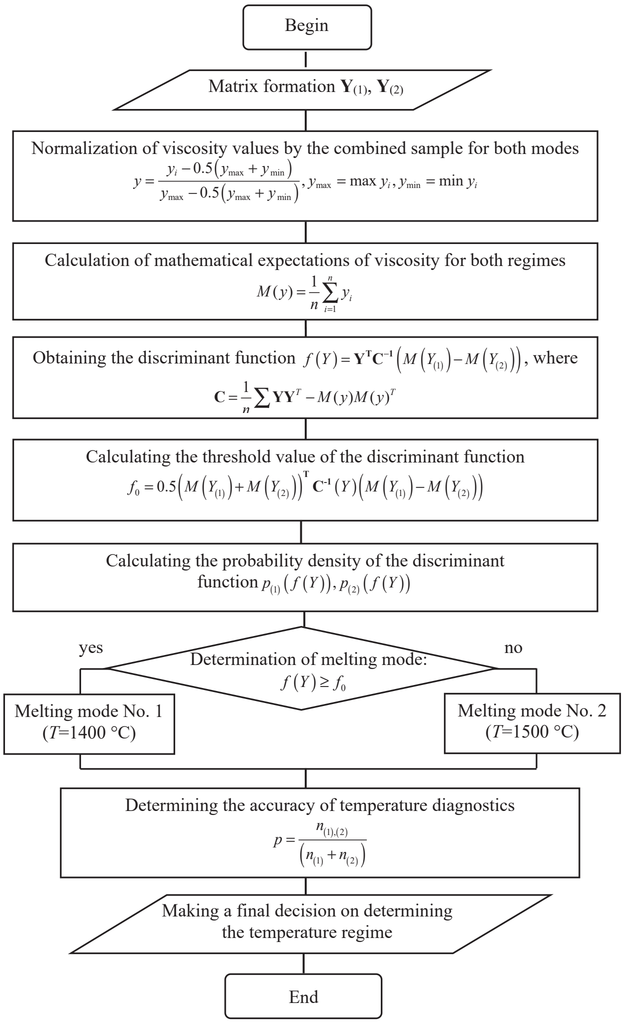

Fig. 2. Algorithm for identifying temperature regime

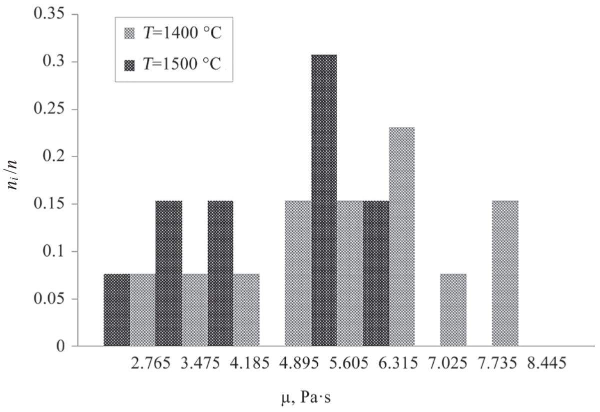

Fig. 3. Histograms of the probability density distribution values of the discriminant function

Fig. 3 shows that the histograms are shifted relative to each other, and a lower temperature corresponds to a higher viscosity – the histogram for temperature regime No. 1 is to the right of the histogram for temperature regime No. 2. Based on calculations according to the algorithm shown in Fig. 1, the following criterion for identifying temperature regime No. 1 was determined:

$$-10.3893\,y \ge 2.08826. \tag{4}$$

In other cases, the temperature regime is No. 1.

Criterion (4) is given in normalized form. In its natural form, it is written as follows:

$$-0.15244\mu \ge -0.56783. \tag{5}$$

Using criterion (4) or (5) allows identifying the temperature regime with an accuracy of 96 %.

The relationships between variables and the identification procedure are conventionally represented in the form of a structural diagram shown in Fig. 4.

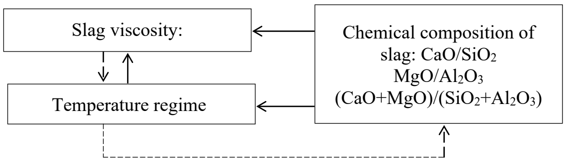

Fig. 4. Structural diagram with presentation of the procedure of identification of temperature regime

Limitations of the research are that too little experimental data was used to build models, and also that to identify the temperature regime by the composition of slag based on the determination of viscosity, it is necessary to solve a system of equations with three variables. This requires a series of additional experiments, which may become a direction of development of the research in the future.

4. Conclusions

The proposed criterion for assessing the temperature regime of melting by the viscosity of slag allows to identify the temperature regime of melting with an accuracy of 96 %. This result is due to the proposed two-stage procedure, in which the first stage is the construction of mathematical models that describe the influence of the composition of slag on viscosity, and the second is the construction of a criterion based on the density distribution of the discriminant function for both temperature regimes. Using the obtained criterion also makes it possible to determine the areas of chemical compositions, by which the temperature regime can also be identified and, thereby, periodically monitor the quality of the functioning of the temperature control circuit in the melting control system.

Conflict of interest

The authors declare that they have 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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The research was performed without financial support.

Data availability

The manuscript has no associated data.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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✉***Denys Nikolaiev,*** *PhD Student, Department of Foundry, National Technical University "Kharkiv Polytechnic Institute", Kharkiv, Ukraine, ORCID: https://orcid.org/0000-0002-8324-1760, e-mail: nikolaev@entc.com.ua*

Vadym Selivorstov, *Doctor of Technical Sciences, Professor, Department of Foundry Production, Ukrainian State University of Science and Technologies, Dnipro, Ukraine, ORCID: https://orcid.org/0000-0002-1916-625X*

Yuriy Dotsenko, *PhD, Associate Professor, Department of Foundry Production, Ukrainian State University of Science and Technologies, Dnipro, Ukraine, ORCID: https://orcid.org/0000-0002-7734-7884*

Oleksandr Dzevochko, *PhD, Associate Professor, Head of Department of Technological Systems Automation and Environmental Monitoring, National Technical University "Kharkiv Polytechnic Institute", Kharkiv, Ukraine, ORCID: https://orcid.org/0000-0002-1297-1045*

Alevtyna Pereverzieva, *Assistant, Department of Technological Systems Automation and Environmental Monitoring, National Technical University "Kharkiv Polytechnic Institute", Kharkiv, Ukraine, ORCID: https://orcid.org/0000-0003-2072-2521*

Alona Dzevochko, *PhD, Associate Professor, Department of Technological Systems Automation and Environmental Monitoring, National Technical University "Kharkiv Polytechnic Institute", Kharkiv, Ukraine, ORCID: https://orcid.org/0000-0001-5988-5577*

✉*Corresponding author*