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DETERMINATION OF CONDITIONS FOR PREVENTING CHEMICAL WEAR OF INDUCTION FURNACE LINING IN THE "CUPOLA FURNACE – INDUCTION FURNACE" DUPLEX PROCESS

The object of research is the melting of cast iron in the "cupola furnace – induction furnace" duplex process. The need to study such a duplex process is dictated by the condition of ensuring the required quality of cast iron in the event that a low-quality or uncontrolled charge is used. This condition cannot be met if the induction furnace is used as the only melting unit. But the problem is that in the process of induction melting of cast iron, in particular at the stage of overheating and holding the melt, a crucible reaction may begin, which leads to chemical wear of the lining. The need to reduce the carbon content in the melt discharged from the cupola furnace requires an increase in temperatures, which creates risks for the onset of a crucible reaction.

Based on statistical calculations of cupola melting parameters, it was found that in the melt discharged from the cupola furnace into the induction furnace, the average carbon content is C = 3.47% with a standard deviation S_C = 0.14%, and the average silicon content is Si = 2.05% with a standard deviation S_{Si} = 0.21%. At the same time, with a probability of 96%, the carbon content is C = (3.33–3.75)%, and the silicon content corresponds to the range Si = (1.84–2.46)% with a probability of 98%. It was found that the equilibrium constant is in the range (0.15–0.21) with a probability of 97.8% at an average temperature T = 1355°C with a standard deviation of temperature S_T = 6°C. With such melt parameters, which are supplied to the induction furnace, the risks of the onset of a crucible reaction do not arise. It was determined that even at temperature regimes sufficient to remove FeO, the risk of the onset of a crucible reaction is minimal. In order to ensure conditions that prevent the onset of a crucible reaction, the following recommendations should be followed for the content of carbon and silicon in high-temperature melting when the temperature is in the range T > 1480°C: C > 0.3% and Si < 0.3%.

The results of the study can be used in the melting sections of foundries equipped with cupola furnaces and induction furnaces.

Keywords: *"cupola furnace – induction furnace" duplex processes, crucible reaction, chemical wear of the lining, poor-quality charge.*

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1. Introduction

Induction melting is very demanding on the charge quality due to the complexity, and sometimes the impossibility, of ensuring the conduct of physicochemical processes in the melt in the required volume. Therefore, in the absence of a high-quality charge, the possibilities of induction melting to ensure the production of high-quality cast iron are limited. The solution options are to use an induction furnace as a secondary unit, where the first unit can be either a cupola or an electric arc furnace. These primary units produce cast iron, which can already be used in an induction furnace for further technological processing, in particular, bringing the temperature to a given value and stabilizing the chemical composition. But for this, such technological melting modes must be implemented in the primary units and such control of the melting processes must be implemented that ensure maximum proximity of cast iron to the quality requirements. Such requirements as the metallurgical component of quality, according to [1], are determined by compliance with the given content of chemical elements and temperature.

Ensuring closeness in terms of iron quality indicators when using a cupola furnace as a primary furnace becomes possible when choosing the optimal control of the cupola process. Examples of such control can be two-level control of the charge loading and air supply system [2] and the influence on the thermodynamic processes occurring in the cupola furnace [3]. In addition, it is possible to improve the fuel supply processes by rationalizing the design of devices for introducing fuel and post-regeneration dust through tuyeres [4]. Such options assume the presence of mathematical models that link the technological modes of melting and the design parameters of the cupola furnaces in which these modes are used, and allow for indirect control of the processes [5, 6]. In this case, the most important is the control and regulation of the temperature regime in the furnace [7]. In the case of using an electric arc furnace as a primary metallurgical unit, the main factors are the control of thermal regimes, which depend on the selected transformer power and electric arc parameters. Such control is carried out by optimal controllers [8–10] and appropriate computer-integrated solutions [11]. It is worth noting that the electric arc furnace is the most appropriate primary unit if the charge is not

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controlled for quality, or its quality is too low. Therefore, it is in such a furnace that it is possible to ensure the quality of cast iron close to the requirements, in particular, taking into account the requirements for several quality indicators [12].

In the case of ensuring the quality of the melt close to the requirements by the primary furnace, the main task of the induction furnace becomes the holding of the melt at a given temperature in order to stabilize the chemical composition. Therefore, at this stage of the process, it is important to control the temperature regime in the furnace [13–15] taking into account the peculiarities of the process. They consist in the fact that the process is carried out with a constant residue of the melt and the addition of new portions of the melt from the primary furnace. This affects the kinetics of the chemical composition [16], and, accordingly, the formation of the final composition of cast iron, which must correspond to the specified range for each element.

The described technological options for producing cast iron have one common feature – the need to control and regulate the temperature regime in furnaces, which affects the course of physicochemical processes. And it is with this that the problem areas in the context of the research results presented in the analyzed sources are connected. This is the quantitative uncertainty of the effect of temperature on the chemical composition of cast iron at any stage. In particular, it is manifested due to the complexity of temperature control and the ambiguous effect on the content of each chemical element, taking into account the formation of non-metallic inclusions in the melt. In the case of using a cupola furnace as the primary furnace, another problem is inherent – the overestimated carbon content, which must be reduced in the induction furnace. In this case, it should be additionally taken into account that an irrational temperature regime at certain ratios of carbon and silicon can lead to the development of a reaction of interaction between carbon and silica of the acidic lining, which directly leads to its chemical wear.

The object of the research is the melting of cast iron in the "cupola furnace – induction furnace" duplex process.

The aim of the research is to determine the conditions for preventing chemical wear of the induction furnace lining in the "cupola furnace – induction furnace" duplex process. This will make it possible to choose rational options for melting control.

To achieve the aim, the following objectives were solved:

1. To determine the risks of a crucible reaction in an induction furnace based on the results of a statistical analysis of the chemical composition and temperature of cast iron discharged from the cupola furnace into the induction furnace.
2. To determine the key factors and the range of their permissible values, under which the development of a crucible reaction in an induction furnace is possible under high-temperature melting conditions.

2. Materials and Methods

The functional diagram implementing the object of research is shown in Fig. 1.

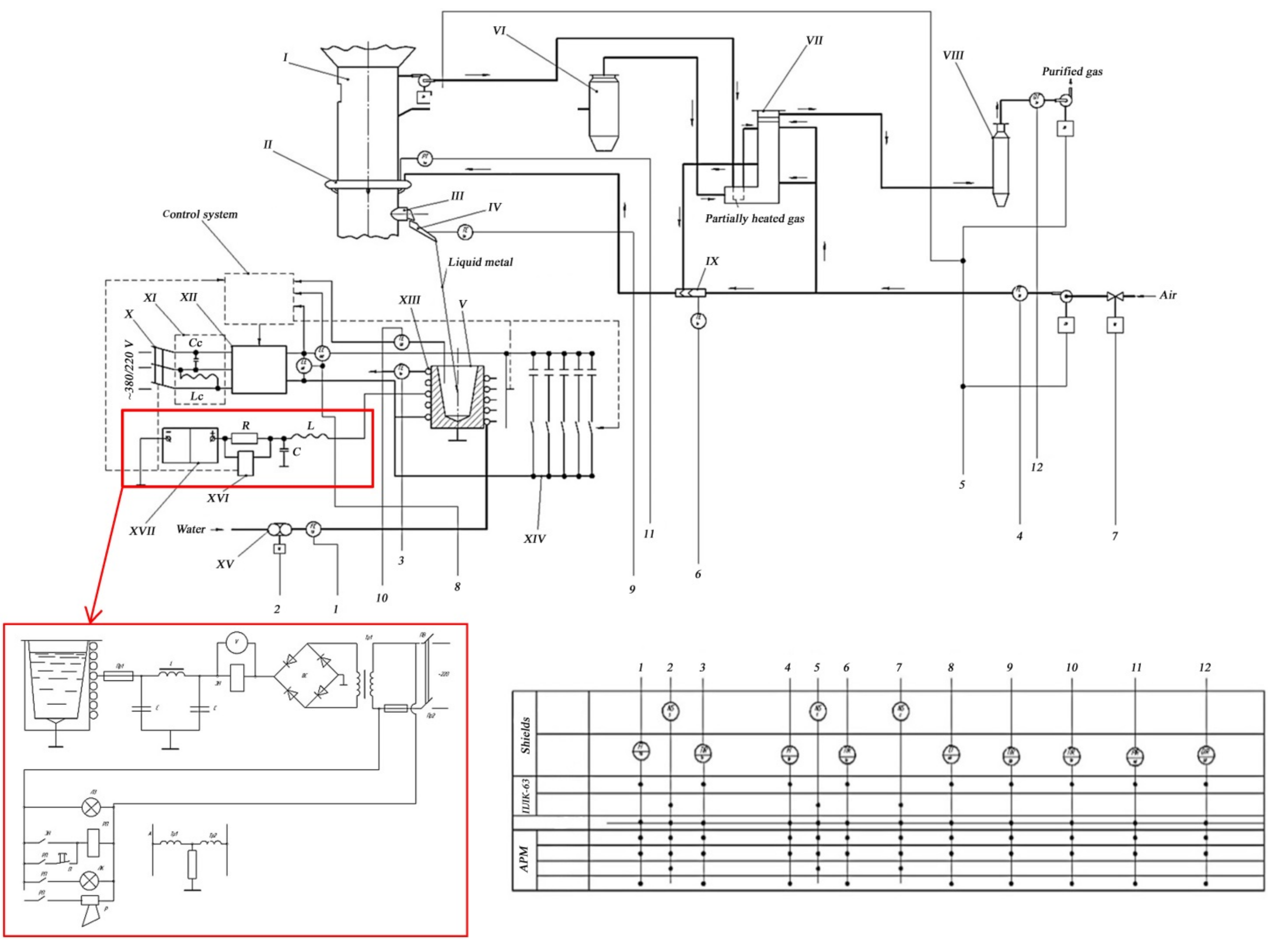

Fig. 1. Functional diagram of the "cupola furnace – induction furnace" duplex melting process:
I – cupola furnace, II – tuyeres, III – accumulator, IV – chute, V – induction furnace, VI – cyclone, VII – radiation recuperator,
VIII – wet scrubber, IX – air mixer, X – power switch, XI – balancing device, XII – regulating transformer with voltage step switch,
XIII – inductor, XIV – capacitor bank, XV – cooling system pump, XVI – blocking and signaling relay,
XVII – DC source for monitoring the state of the crucible and inductor insulation

The red color indicates the circuit element that monitors the state of the acidic lining, which can be damaged due to the crucible reaction, which leads to its chemical wear

$$2[C]+\langle SiO_2\rangle \rightleftarrows [Si]+2\{CO\}, \qquad (1)$$

where [C], [Si] – carbon and silicon content in the melt, $\langle SiO_2\rangle$ – silicon dioxide lining, {CO} – carbon monoxide, which enters the atmosphere.

This is a typical diagram of an alarm device, which contains two blocks. The first block contains control equipment, auxiliary circuits and power circuits of devices. The second block is a low-frequency filter connected to the first block and inductor by wires. The alarm device is triggered when molten metal touches the inductor, or when the insulation of the inductor, capacitors, secondary winding of the power transformer or cables is damaged.

To analyze the indicators of cupola melting, the results of experimental and industrial studies presented in [17] were used, and to analyze the indicators of induction melting, the systematized data presented in [18] were used.

3. Results and Discussion

Fig. 2 and 3 show histograms of the distribution of carbon and silicon content in the melt discharged from the cupola furnace, obtained from a sample of 45 melts, and Fig. 4 shows histograms of the melt temperature distribution.

From the data in Fig. 2 it follows that with a probability of 69% C = (3.47–3.61)% and with a probability of 96% C = (3.33–3.75)%. At the same time, the average carbon content C = 3.47% with a standard deviation S_C = 0.14%. From Fig. 3 it is seen that with a probability of 98% Si = (1.84–2.46)%. At the same time, the average silicon content Si = 2.05% with a standard deviation S_{Si} = 0.21%.

The histogram in Fig. 4 indicates that the distribution law may differ from the normal one, but with a probability of 62% the melt temperature is T = (1355–1361)°C. At the same time, the average temperature T = 1355°C with a standard deviation S_T = 6°C.

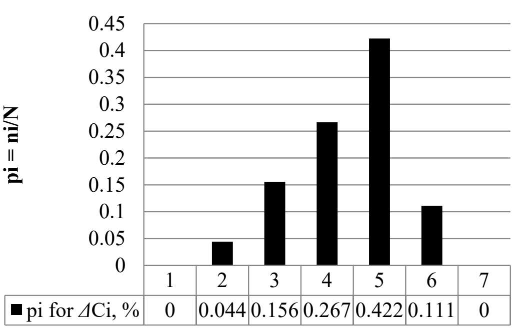

Fig. 2. Distribution of carbon content in the melt discharged from the cupola furnace: $\Delta C = S_C$ = 0.14%, C = 3.47 ± $3S_C$

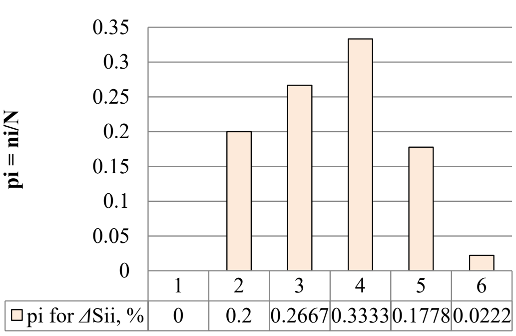

Fig. 3. Distribution of silicon content in the melt discharged from the cupola furnace: $\Delta Si = S_{Si}$ = 0.21%, Si = 2.05 ± $3S_{Si}$

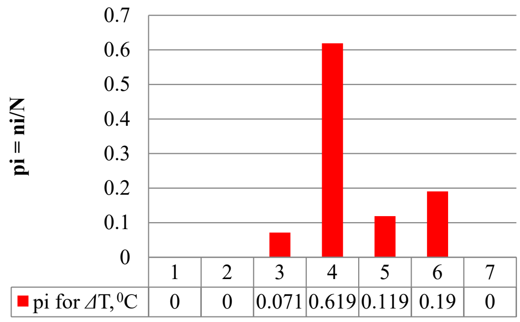

Fig. 4. Distribution of melt temperature discharged from the cupola furnace: $\Delta T = S_T$ = 6°C, T = 1355 ± $3S_T$°C

Such a melt is fed into an induction furnace, in which the crucible reaction can begin to develop, the rate constant of which is determined from the well-known formula

$$\lg\frac{Si}{C^2}=17.62-\frac{32000}{T_{Eq}}, \qquad (2)$$

where Si/C^2 – the ratio that determines the equilibrium constant of the reaction (1), T_{Eq} – the equilibrium temperature in the system, K.

Fig. 5 shows a histogram of the distribution Si/C^2.

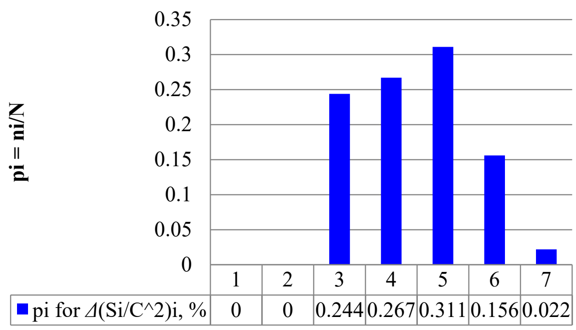

Fig. 5. Distribution histogram Si/C^2: $\Delta Si/C^2 = S_{Si/C^2}$ = 0.021, Si/C^2 = 0.171 ± $3S_{Si/C^2}$

From the data of Fig. 5 it follows that with a probability of 97.8% $Si/C^2=(0.15-0.21)$ at temperatures T = (1349–1367)°C. This region is shown in Fig. 6 together with the curve reflecting the equilibrium according to (2).

As can be seen from Fig. 6, the development of reaction (1) when receiving molten iron from the cupola furnace by an induction furnace cannot begin. But to remove excess carbon, it is necessary to increase the temperature, so there may be risks of the development of reaction (1). In this case, temperature plays an important role in the removal of inclusions, the main of which is FeO. This is ensured by holding the melt in an induction furnace at a given temperature. Fig. 7 presents the temperature regimes for removing FeO from the melt when holding at specified temperatures for an interval of 10 min, obtained based on data [18], as well as the equilibrium curve of the reaction (1).

It follows from Fig. 7 that even at temperature regimes sufficient for removing FeO, the risk of starting reaction (1) is minimal. The problem can arise only in the event of a situation where the temperature increase to 1480°C and above is carried out according to the ratio $Si/C^2>0.33$. This can happen when the melt contains C < 0.3% and Si > 0.3%.

The results obtained indicate that the chemical composition and temperature of the melt discharged from the cupola furnace do not create risks for chemical wear of the induction furnace lining. Instead, in the case of switching to a high-temperature regime during the melt holding process in induction furnaces, the carbon and silicon content should be controlled and appropriate corrective additives should be introduced.

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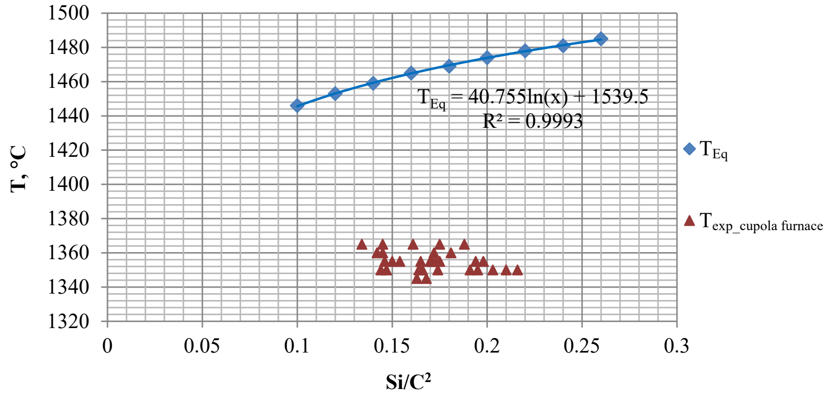

Fig. 6. The equilibrium curve of the crucible reaction and the actual indicators of the melt discharged from the cupola furnace into the induction furnace

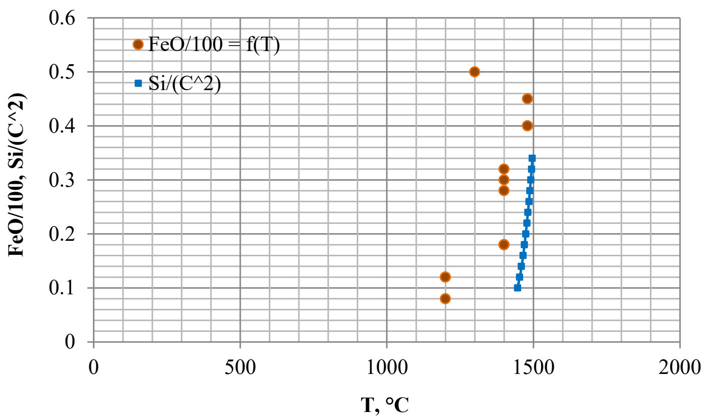

Fig. 7. Temperature regimes for removing FeO from the melt and the equilibrium curve

The results obtained are limited by the considered temperature ranges and ranges of chemical element contents, therefore, in further studies, these ranges should be expanded. A promising direction for further development of the research is also the construction of kinetic curves describing the oxidation and reduction processes in the induction furnace, to determine rational options for controlling the considered duplex process. Such control should be based on mathematical models that represent the dependence of the content of chemical elements on time within the melting cycles. That is, the models are kinetic equations, where the factor influencing the course of reactions is temperature. The control is the power supplied to the furnace, depending on the initial chemical composition and temperature of the melt discharged from the cupola furnace. In this case, the mass of the remaining melt in the induction furnace, its chemical composition and temperature should also be taken into account.

4. Conclusions

1. It has been established that in the melt discharged from the cupola furnace into the induction furnace, the average carbon content is C = 3.47% with a standard deviation S_C = 0.14%, and the average silicon content is Si = 2.05% with a standard deviation S_{Si} = 0.21%. With such indicators, the equilibrium constant of the reaction of the interaction of carbon and silica of the acid lining of the induction furnace is in the range (0.15–0.21) with a probability of 97.8% at an average temperature T = 1355°C with a standard deviation of temperature S_T = 6°C. This does not create risks for the onset of the crucible reaction.

2. It has been determined that even at temperature regimes sufficient to remove FeO, the risk of the onset of the crucible reaction is minimal. However, during the melting process, the ratio of carbon and silicon should be controlled at temperatures at which the melt is held in the induction furnace in order to reduce the number of non-metallic inclusions. The range of permissible ratios is given by the condition C > 0.3% and Si < 0.3% for high-temperature melting when the temperature is in the range T > 1480°C.

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.

Authors' contributions

Denis Nikolaev: Writing – original draft, Methodology, Data curation, Validation, Supervision; ***Vadym Selivorstov***: Conceptualization, Methodology; ***Yuriy Dotsenko***: Conceptualization, Validation; ***Iryna Osypenko***: Data curation, Writing – review and editing; ***Eugene Kuznetsow***: Data curation, Validation.

References

1. Demin, D., Frolova, L. (2024). Construction of a logical-probabilistic model of casting quality formation for managing technological operations in foundry production. *EUREKA: Physics and Engineering, 6*, 104–118. https://doi.org/10.21303/2461-4262.2024.003518
2. Demin, D. (2023). Experimental and industrial method of synthesis of optimal control of the temperature region of cupola melting. *EUREKA: Physics and Engineering, 2*, 68–82. https://doi.org/10.21303/2461-4262.2023.002804
3. Ajah, S. A., Idorenyin, D., Nwokenkwo, U. C., Nwigwe, U. S., Ezurike, B. O. (2021). Thermal Analysis of a Conventional Cupola Furnace with Effects of Excess Air on the Flue Gases Specific Heat. *Journal of Materials and Environmental Science, 12 (2)*, 192–204.

4. Jopkiewicz, A., Podrzucki, C. (2007). Tendencies to the Improvement of the Cupola Process. *Archives of foundry engineering, 13 (3),* 61–70.
5. Nikolaiev, D., Selivorstov, V., Dotsenko, Y., Dzevochko, O., Pereverzieva, A., Dzevochko, A. (2025). Identification of temperature in cupola furnace based on the construction of the "slag composition – slag viscosity" model. *Technology Audit and Production Reserves, 1 (1 (81)),* 29–33. https://doi.org/10.15587/2706-5448.2025.322458
6. Nikolaiev, D. (2024). Construction of a cupola information profile for further modeling for the purpose of controlling melting processes. *ScienceRise, 2*, 3–14. https://doi.org/10.21303/2313-8416.2024.003674
7. Demin, D. (2025). Optimization of parameters of the cupola melting by the criterion of the maximum cast iron temperature. *EUREKA: Physics and Engineering, 2,* 158–165. https://doi.org/10.21303/2461-4262.2025.003712
8. Demin, D. A. (2012). Synthesis of optimal temperature regulator of electroarc holding furnace bath. *Scientific Bulletin of National Mining University, 6,* 52–58.
9. Demin, D. (2014). Mathematical description typification in the problems of synthesis of optimal controller of foundry technological parameters. *Eastern-European Journal of Enterprise Technologies, 1 (4 (67)),* 43–56. https://doi.org/10.15587/1729-4061.2014.21203
10. Demin, D. (2013). Adaptive modeling in problems of optimal control search termovremennoy cast iron. *Eastern-European Journal of Enterprise Technologies, 6 (4 (66)),* 31–37. https://doi.org/10.15587/1729-4061.2013.19453
11. Demin, D. (2014). Computer-integrated electric-arc melting process control system. *Eastern-European Journal of Enterprise Technologies, 2 (9 (68)),* 18–23. https://doi.org/10.15587/1729-4061.2014.23512
12. Demin, D. (2017). Synthesis of optimal control of technological processes based on a multialternative parametric description of the final state. *Eastern-European Journal of Enterprise Technologies, 3 (4 (87)),* 51–63. https://doi.org/10.15587/1729-4061.2017.105294
13. Demin, D. (2020). Constructing the parametric failure function of the temperature control system of induction crucible furnaces. *EUREKA: Physics and Engineering, 6,* 19–32. https://doi.org/10.21303/2461-4262.2020.001489
14. Stanovska, I., Duhanets, V., Prokopovych, L., Yakhin, S. (2021). Classification rule for determining the temperature regime of induction gray cast iron. *EUREKA: Physics and Engineering, 1,* 60–66. https://doi.org/10.21303/2461-4262.2021.001604
15. Penziev, P., Lavryk, Y. (2023). Diagnostics of the temperature condition of cast iron melting in induction furnaces by the content of SiO_2 and CaO in slag. *ScienceRise, 1,* 14–20. https://doi.org/10.21303/2313-8416.2024.003558
16. Demin, D., Domin, O. (2021). Adaptive technology for constructing the kinetic equations of reduction reactions under conditions of a priori uncertainty. *EUREKA: Physics and Engineering, 4,* 14–29. https://doi.org/10.21303/2461-4262.2021.001959
17. Lysenkov, V. Yu. (2025). Systematyzovani dani po khimichnomu skladu chavunu vahranochnoi plavky dlia vyhotovlennia tonkostinnykh vylyvkiv. *Teoretychni ta praktychni doslidzhennia molodykh vchenykh.* Kharkiv: NTU "KhPI", 735–736.
18. Lavryk, Ye. Ye. (2025). Vyznachennia vplyvu rezhymiv induktsiinoi plavky na kilkist nemetalevykh vkliuchen v ridkomu chavuni. *Teoretychni ta praktychni doslidzhennia molodykh vchenykh.* Kharkiv: NTU "KhPI", 732–733.

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