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CONSTRUCTION OF A KINETIC EQUATION OF CARBON REMOVAL FOR CONTROLLING STEEL MELTING IN THE METALLURGICAL SYSTEM "CUPOLA FURNACE – SMALL CONVERTER"

The object of research in the paper is the process of steelmaking in a small converter, which works in tandem with a cupola furnace.

The existing problem is that the control of the process of obtaining steel in an oxygen converter is complicated by the need to determine in real time the current chemical composition of the melt, in particular carbon. This is due to the fact that the rate of carbon removal is too high, as a result of which the process of carbon removal is transient. Therefore, it is too difficult to implement regulation based on feedback on continuous measurement.

The presence of the specified problem requires solutions related to the possibilities of developing or improving software control of the process.

It is shown that in certain sections of the process within each time section of oxygen purging of the melt in the converter, the kinetic curve has a linear form with a constant coefficient value in front of the inlet mine. But the value of the initial coefficient for each equation that describes the process within its limits changes. This allows to state that in case of a change in the initial condition, the kinetic curves shift relative to each other in parallel. On this basis, a system of equations has been constructed that describes the process of carbon removal in a small oxygen converter that receives liquid iron from a cupola furnace.

It has been shown that to use the obtained system of equations, it is necessary to know the initial carbon content in the melt discharged from the cupola furnace, and it depends on the method of oxygen supply to the cupola furnace. Based on the modeling of this process in two variants – using a "sharp blow" and supplying oxygen to the air blown into the tuyeres, a nomogram has been constructed. It allows to determine the initial carbon content for the practical use of the obtained system of equations.

Using the obtained system makes it possible to determine the time after which oxygen cutoff should be made. This will allow to decide to implement software control of the melt blowing process in the converter.

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

Keywords: *cupola melting, converter, oxygen blowing, sharp blast in a cupola furnace, kinetic equations.*

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1. Introduction

Modern approaches to the management of metallurgical units and processes consist in considering these objects as controlled systems that can be implemented on the basis of computer-integrated solutions. This involves the creation of multi-level control systems aimed at automating the melting processes as much as possible and ensuring quality improvement. In confirmation of this, a project of a fuzzy temperature control system in a cupola furnace can be provided as a means of influencing other melting parameters in order to ensure a given course of chemical reactions in the furnace [1].

The software package for controlling the melting process is presented in work [2], and the structures of the control system and technical solutions for the layout of technical automation tools are given in works [3, 4]. The problem of technical implementation of tools and systems for controlling the cupola melting process is the objective difficulties of continuous parameter control, which is not solved in the mentioned works. These issues are partially considered in the work [5], which proposes a hardware system for assessing the reliability of the readings of primary converters of cupola furnaces and an evaluation algorithm. An option for solving the problem may be indirect determination of melting parameters based on the construction of mathematical models of the process [6], which, as a result of implementation, may allow to improve the quality of cast iron as a component of the quality of finished castings [7].

This allows to speak about the presence of unresolved issues regarding the possibility of effective control of cupola melting. Thus, if to compare this process with electric arc melting, for which optimal control systems [8, 9] and computer-integrated solutions for process control [10] can be implemented, even under conditions of different final states of the control object [11], cupola melting does not have such capabilities.

A solution option may be to define rational control methods, for example, those based on determining the temperature profile and kinetics of carbon in the melt [12] or two-level control of the charge loading and air supply system [13]. However, the predominantly theoretical nature of these solutions may encounter the need for additional engineering developments for practical implementation. In terms of improving the cupola process, one can mention the work [14], which presents a description of a device for introducing fuel and post-regeneration dust through tuyeres. Solutions aimed at improving a set of design and technological measures [15] or increasing melting performance through influencing the thermodynamic processes occurring in the cupola furnace [16, 17] are also possible. However, when using such approaches, it should be taken into account 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 due to the nature of the process, which involves periodic loading, complexity or impossibility of clearly determining the composition of the charge. Therefore, it is important to take into account the drift factor of process parameters [18] and, taking this into account, adapt the control process according to the principle of analogy of adaptive control of electric arc melting [19].

When considering possible measures aimed at creating computer-integrated control systems, it is necessary to take into account the provision of conditions for the implementation of a closed cycle of the technological process. This means the possibility of recycling emissions from the furnace [20, 21] and indirect control of technological melting modes [22]. The latter is aimed at diagnosing the state of the process based on the analysis of the slag composition and is a development of this idea, also implemented in works [23–25]. If it turns out that the temperature regime does not correspond to the specified one, factors that can exert a controlling influence are determined, among which may be the temperature of heating the air distributed through the tuyeres and the amount of coke [26]. However, the solutions presented in these works consider individual influencing factors. This approach is justified by the real difficulties of building multifactor models suitable for melting control, but requires further development. In particular, it is important to consider the problem in the case when the cupola furnace works in conjunction with another metallurgical unit and is intended not only for melting of cast iron, but is part of the technological process of steelmaking. Such a unit can be a small converter intended for steel production in machine-building enterprises. In this case, there is a need to ensure the chemical composition of cast iron as accurately as possible. This is subject to subsequent purging in the converter to obtain steel, which is carried out using various purging options to ensure a regulated content of chemical elements and the content of gases leaving the converter [27, 28]. It is important to note that these issues are relevant, given that the rate of oxidation processes is very high, and it is very difficult to measure the process parameters, in particular the chemical composition, in a short time with a given accuracy. Therefore, at the moment, the only effective solution is the presence of adequate kinetic models of oxidation, primarily of carbon, which will allow for time control. This problem needs to be solved, so it is advisable to conduct a study devoted to the construction of such a mathematical model.

The aim of research is to construct equations that describe the process of carbon removal in a small oxygen converter, which is a secondary metallurgical unit and receives liquid iron from a cupola furnace.

2. Materials and Methods

The object of research is the process of steelmaking in a small converter, which works in tandem with a cupola furnace, the schematic diagram of which is shown in Fig. 1 [6].

In principle, this process can be implemented in two ways: 1 – molten iron is fed to the converter from the intermediate bath, where the alloy is pre-refined, 2 – molten iron is fed to the converter from the cupola slag collector, in which, in particular, preliminary oxygen purging can be provided.

The converter process is controlled at the automation level by cutting off the oxygen supply. The problem is that the carbon removal rate is too high, as a result of which the carbon removal process is fast-paced, and therefore it is too difficult to implement regulation based on feedback on continuous measurement. Therefore, it was assumed that if there are equations describing the carbon removal process, it is possible to implement program regulation. But for this it is necessary to know the initial chemical state of the iron, the initial carbon content is especially important.

Input data on the rate of carbon removal, the content of CO and CO_2 in the gases leaving the converter, the temperature of cast iron and its carbon content during melting in a cupola furnace were selected from the work [6].

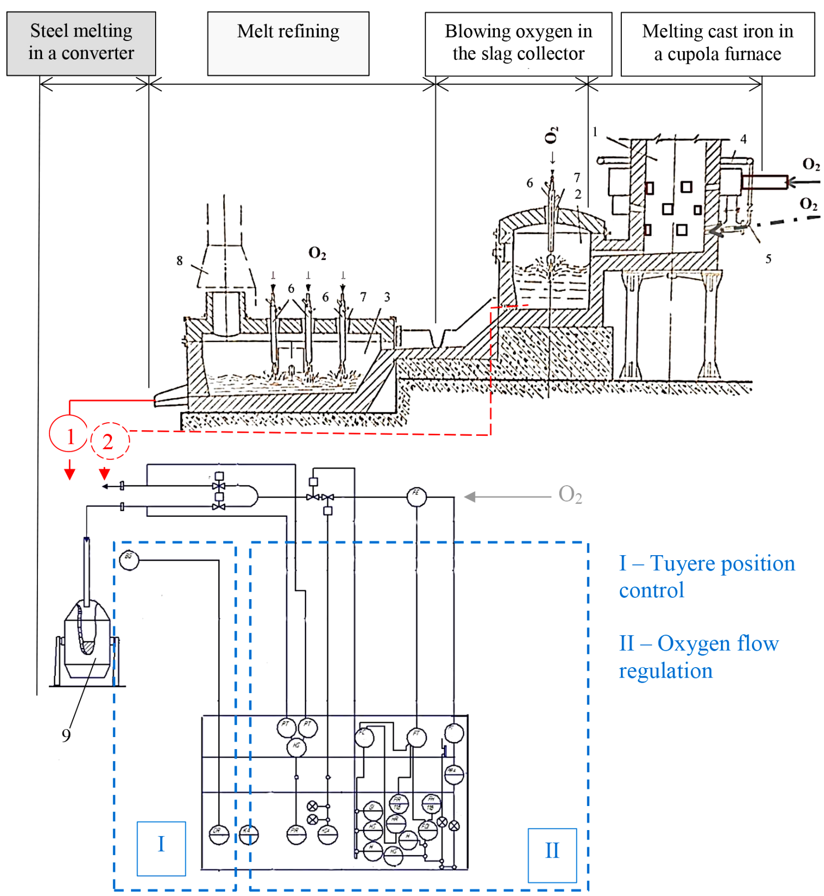

Fig. 1. Scheme of the steelmaking process in a small converter operating in conjunction with a cupola furnace: 1 – cupola furnace, 2 – slag collector, 3 – refining bath, 4 – ring wire for supplying oxygen to the cupola furnace, 5 – nozzle tube for supplying oxygen to the cupola furnace, 6 – retractable water-cooled tuyere for supplying oxygen to the liquid metal bath, 7 – refrigerator, 8 – pipe with an umbrella for removing gases, 9 – converter

The equations for determining the patterns of changes in the process parameters were built based on the least squares method.

3. Results and Discussion

Fig. 2 shows a diagram of the change in the rate of carbon removal process at the stages of melt purging in the converter, from which it follows that at the considered stages the dependence of the carbon content on time will have a different angle of inclination (Fig. 3).

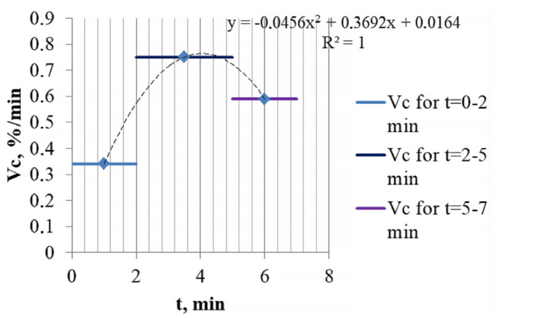

Fig. 2. Diagram of the change in the rate of carbon removal in the converter

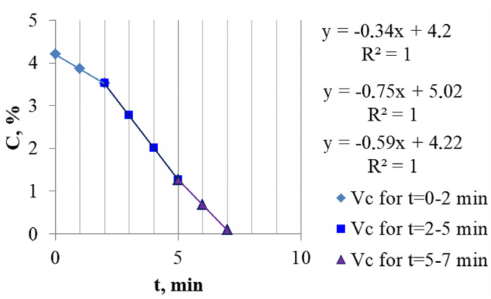

Fig. 3. Kinetic curve of the carbon content in the melt during the blowing process in the converter

Fig. 3 shows that in certain sections of the process within each section, the kinetic curve has a linear form with a constant coefficient value in front of the inlet variable. But in different sections this pattern is not maintained. As for the initial coefficient for each equation that describes the process within its limits, it is variable. This allows to state that in the event of a change in the initial condition, i. e. a different value of the carbon content in the molten iron entering the converter, the curves will shift relative to each other in parallel. This means that the equations that describe the carbon removal process can be represented in the form of the following system:

$$C = \begin{cases} C_0 - 0.34t \text{ for } t \in [0;2], \\ C_0 - 0.75t \text{ for } t \in [2;5], \\ C_0 - 0.59t \text{ for } t \in [5;7]. \end{cases} \quad (1)$$

Equation (1) can be used to determine the oxygen cut-off time depending on the requirement for the carbon content in the steel. But in order for the obtained result to be correct, it is necessary to determine the initial carbon content C_0 with the greatest possible accuracy. To do this, it is necessary to have a model that allows to predict this value. It is important to note that it will depend on how the melting process in the cupola furnace takes place. If the intensification of the melting process occurs by enriching the air supplied to the cupola furnace with oxygen, then it is fundamentally important to consider two options for the process. These options are: supplying oxygen directly to the tuyeres, i. e. "sharp blast" (conditionally named Experiment No. 1), and supplying oxygen to the air duct, i. e. mixing oxygen with the air supplied to the cupola furnace (conditionally named Experiment No. 2). The first is indicated in Fig. 2 by a dotted arrow to visualize the O_2 supply, the second is a solid arrow.

According to the selected option, the temperature of the cast iron will change. This means that the carbon content in the cast iron will also change. Taking this into account, a nomogram can be constructed that allows to calculate the predicted carbon content C_0, depending on the method of supplying oxygen to the cupola furnace (Fig. 4).

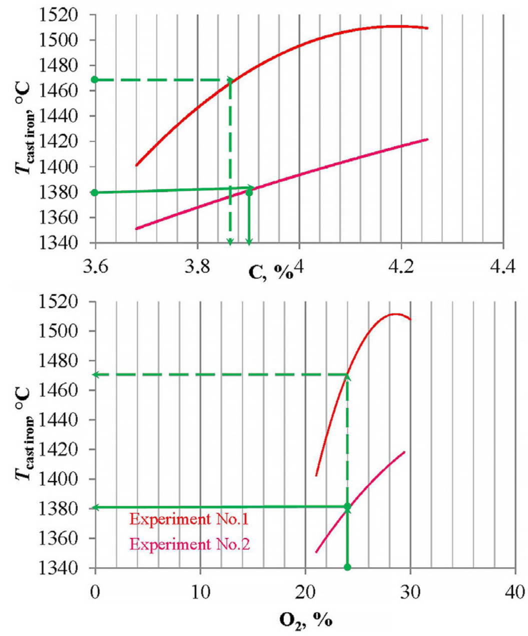

Fig. 4. Nomogram for determining C_0

In conclusion, the calculation of C according to formula (1) will also allow determining kinetic curves for determining CO and CO_2 in the gases leaving the converter. An example of such equations is given in Fig. 5.

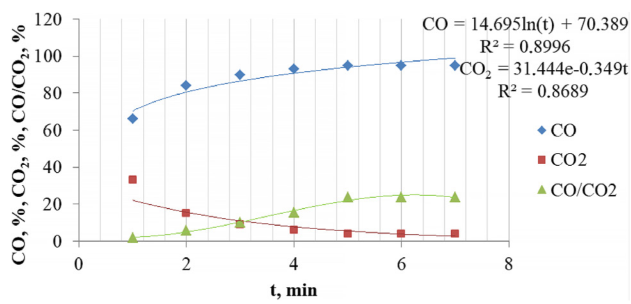

Fig. 5. Kinetic curves for determining CO and CO_2 in gases leaving the converter

Unlike the works devoted to the efficiency of melting in separate units and the control of the corresponding processes – cupola furnaces [14–17] and converters [27, 28], this study considers a combined process. By obtaining kinetic equations describing the change in carbon content in both technological operations (Fig. 2, 3, formula (1)), it is possible to determine the time required for carbon separation during the process of blowing the melt in the converter. Accordingly, it is possible to rationalize the process of melting control. It is important to note that the method of supplying oxygen to the cupola furnace is of fundamental importance, on which the carbon content in the molten iron depends, i. e. the formation of the initial condition for determining the time to the cut-off of oxygen supplied to the converter. This is explained by the fact that the temperature of the iron changes with different oxygen supply options. Thus, in the case of "sharp blowing" (Experiment No. 1),

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the temperature of the cast iron is higher and C_0 is lower than when oxygen is supplied to the air (Experiment No. 2).

The research results are limited to variations in the input variables and design parameters of cupola furnaces and converters.

A possible direction for the development of the study is to expand the range of design and technological options for cupola furnaces and converters and obtain a wider set of data from experimental industrial smelters.

4. Conclusions

Equations were obtained that describe the process of carbon removal during oxygen blowing of molten iron in a converter operating in conjunction with a cupola furnace. These equations represent a system that describes each time section of the process. This system can be used to determine the time of oxygen supply cutoff and thus implement software control of the smelter. It is shown that to use this system, it is necessary to know the initial carbon content in the melt discharged from the cupola furnace, and it depends on the method of oxygen supply to the cupola furnace. Based on the modeling of this process in two variants – using a "sharp blow" and supplying oxygen to the air blown into the tuyeres, a nomogram was constructed. It allows to determine the initial carbon content for the practical use of the resulting system of equations.

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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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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