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DETERMINING CHANGES IN THE TEMPERATURE FIELD OF A GRAPHITIZED HOLLOW ELECTRODE DURING METAL PROCESSING PERIODS IN LADLE-FURNACE

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This paper reports an analysis of the process of heating a graphitized hollow electrode (GHE) during steel processing in ladle-furnace. The results of the numerical modeling of electrode operation are given. The data on the temperature field of the electrode were obtained when electricity was supplied and during periods without electrical loading. Values of the Joule heat released at electrode operation during the periods of metal heating in ladle-furnace were calculated; they amounted to 1.11–1.15 MW/m^3. Coefficients of the heat transfer by convection have been calculated for the inner and outer GHE surface: 1.60 and 1.80, and 5–17 W/(m^2·°C), respectively. Values of the electrode temperature gradient in the high-temperature zone were obtained, which, for the first heating period, reached 8,286 °C/m, for the third – to 6,571 °C/m. It was established that during the cooling periods of the electrode, the temperature gradient is significantly reduced and amounts to the inner surface of 379 °C/m; to the outer surface – 3,613 °C/m; the vertical plane to the end of the electrode – 1,469 °C/m. The directions to improve the installation's thermal work and reduce its resource intensity during out-of-furnace processing of steel have been defined.

It has been determined that during the periods of electrode operation with current supply, significant values of the temperature gradient are observed, which are concentrated in the end part. During the periods of operation without current supply, a locally overheated zone forms, taking the shape of a torus flattened along the axis, which is created as a result of the accumulation of heat from the preceding period. The data have been acquired on the effect exerted by the gas supply through a hollow electrode on the parameters of formation of the high-temperature GHE regions. It has been shown that the supply of neutral gas through a graphitized hollow electrode at a flow rate of 0.05 m^3/min shifts the high-temperature zone to the periphery by 3.5–4.2 mm, as well as reduces its height by 1.0–1.2 mm.

The study reported here could make it possible to calculate expedient gas and material consumption for controlling the oxidation of metal and slag, to reduce the consumption of graphitized electrodes, to bring down energy- and resource costs for metal production

Keywords: numerical modeling, ladle-furnace, graphitized hollow electrode, temperature gradient, boundary conditions

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1. Introduction

The steelmaking complex is characterized by the application of scientific and technical advances aimed at reducing energy and resource costs while improving the quality and volume of production. One of the priority areas of steelmaking at present is out-of-furnace steel processing, which resolves a fairly significant range of issues to improve the quality of metal and enhance the performance of steelmaking units.

The improvement of out-of-furnace steel processing technologies is associated with a wide range of theoretical studies that could make it possible to obtain a mathematical and physical description of the processes of out-of-furnace metal processing and ensure their practical implementation in the industry. The key operations of out-of-furnace steel processing are its heating and blowing it with inert gas through submersible lances or bottom blowing devices in a ladle.

The main source of thermal energy for heating steel during out-of-furnace processing is an electric arc, which is generated using three graphitized electrodes (GEs). The cost of electrodes for steel smelting is one of the essential consumption items in finished products, which is why it is a relevant task related to reducing the cost of finished articles is to decrease the specific consumption of electrodes.

During the high-temperature heating of GE, it undergoes physical and chemical destruction, due to the formation of locally overheated zones in the volume; in addition, its surface is oxidized by gases that are released during heating. At present, there are no reliable data on the operation of hollow electrodes during the out-of-furnace steel processing. There are objective difficulties associated with determining the rational conditions for the supply of materials and gases through the opening of an electrode and determining their effect on the temperature state of the electrode body.

Given this, it is a relevant task to assess the temperature field throughout the volume of the graphitized electrode during different periods of steel processing in ladle-furnace.

2. Literature review and problem statement

Paper [1] shows that the main operations during the out-of-furnace steel processing are refining, deoxidation, alloying, and modification. The successful execution of these operations involves inert gas blowing through the bottom blowing devices of a ladle. However, the issue of compensation for heat loss when using gases remains unresolved; the authors do not explain the achievement of the specified mass exchange indicators.

The option of compensation for heat loss during the out-of-furnace metal processing involving inert gases is the use of thermal energy generated by the electric arc, which forms by means of three graphitized electrodes (GEs) [2]. However, the cited work does not report detailed data on the use of reserves in the energy potential of the electric arc and the way it could affect the cost of metal.

The authors of works [3, 4] provide data on the cost of electrodes during steel smelting and show that this value is 8–12.5 % in the cost of steel; it depends primarily on the consumption of the electrode. In this case, they give data that are characteristic only of metal smelting in electric furnaces and cannot be used in full for metal processing in ladle-furnace.

The results of study [5] show that the basic factors that determine electrode consumption are its physical and chemical destruction. Physical destruction refers to thermal and mechanical loads, chemical destruction is due to the oxidation of the side surface, the wear of an electrode's end resulting from the sublimation of graphite in an arc. In this case, the authors do not provide data on the predominant impact of the physical or chemical wear of the electrode.

One of the ways to reduce electrode consumption is uneven heating and overheating during operation. Thus, the studies reported in [6, 7] showed that one of the effective techniques to reduce the GE temperature is the evaporative cooling of the side surface; applying a given method made it possible to reduce the electrode consumption by 1.5 times. However, the authors did not provide data on the temperature fields of the electrode under different operating modes.

Works [8, 9] report the analysis of the operation of a graphitized hollow electrode (GHE) during metal processing in ladle-furnace. The positive effect of gas supply through the hole in the electrode on metal processing parameters and consumption is shown. Thus, the conditions of metal desulfurization were improved, the processing time decreased; the tendency to reduce electrode consumption was also noted.

The authors of work [10] confirmed the positive effect of injection of molecular gases on the power of an electric arc stabilized by argon. In particular, there was an increase in the power of the electric arc when blowing 20 % of carbon dioxide. However, the use of this gas inevitably leads to the oxidation of melt components. Thus, during the experiments, the assimilation of oxygen by the melt was 10–28 %, depending on the presence of slag on the metal surface. Good results were also obtained when using 3 % propane and 3 % methane. In this case, the use of methane and propane does not cause significant carbonation of metal since it is inhibited kinetically.

A study into the influence of molecular gas injection on the removal of nitrogen from metal was reported in [11]. Injection of 10 % hydrogen and 5 % methane lead to the formation of cyanide (hydrochloric) acid and ammonia on the metal surface, as a result of which the content of nitrogen in metal decreased from 200 to 20 ppm within 80 minutes. There was also a 2–4 times increase in the hydrogen content in the metal, but, by injecting pure argon at the end of processing, its content returned to its starting content; however, no probability of obtaining the specified concentrations was shown.

The data given by the authors do not fully describe the process of influence of gas supply through the electrode on its temperature characteristics while more attention is paid to technological indicators. That approach does not make it possible to state theoretical prerequisites for determining the patterns of influence exerted by factors on the process of electrode destruction.

Based on our analytical review, the absence of reliable data on the formation of theoretical prerequisites for temperature regimes during the operation of a graphitized hollow electrode has been revealed. At the same time, the effect of gas supply through a hollow electrode on temperature indicators was disregarded, both at the side surface and the inner electrode channel.

The above allows us to assert the relevance of a study aimed at determining the influence of external factors on the temperature indicators of electrode operation during the out-of-furnace metal processing in ladle-furnace.

3. The aim and objectives of the study

The purpose of this study is to numerically simulate the heating of a graphitized hollow electrode to obtain data on the electrode's temperature field during steel processing in ladle-furnace under different conditions of its operation. That would make it possible to calculate the consumption of gas and/or materials that are supplied through a hollow electrode with the possibility of further optimization of the metal processing process in ladle-furnace.

To accomplish the aim, the following tasks have been set:

– to calculate a value of the Joule heat released on the electrode and determine the heat transfer coefficients on the outer and inner surface of the hollow electrode at different periods of operation;

– to determine the indicators of the temperature field of a hollow electrode when supplying neutral gas during metal processing periods in ladle-furnace.

4. Materials and methods to study the temperature field of a graphitized hollow electrode

We calculated the temperature fields of a graphitized hollow electrode (GHE) by feeding argon through it during processing in ladle-furnace, by using software for numerical modeling applying a finite-element method. To describe the thermal processes occurring during the out-of-furnace steel processing, a module was used that makes it possible to calculate a non-stationary heat transfer.

Our calculation is based on solving a Fourier-Kirchhoff equation with an inner heat source, which is a differential energy equation in the Cartesian coordinate system:

$$\frac{\partial t}{\partial \tau}=\frac{\lambda}{C\cdot p}\left(\frac{\partial^2 t}{\partial x^2}+\frac{\partial^2 t}{\partial y^2}+\frac{\partial^2 t}{\partial z^2}\right)+\frac{q_v}{C\cdot p}. \qquad (1)$$

The differential equation is based on the thermal balance equation for an infinitely small body element [12].

Because LF operates under different thermal modes, the simulation of electrode heating included 4 periods: I – heating, II – downtime, III – heating, IV – refining, and replacement of the ladle. During periods II and IV, GHE is not heated.

At the first stage, the following initial conditions were set for calculation [13]: graphite density, 1,700 kg/m^3; the thermal conductivity of graphite was set by the following function: $\lambda(t)=162.82-0.0407t$ W/(m·°C); the specific heat capacity of graphite; $c(t)=681.81+2.6673t-0.0019t^2+$ $+5\cdot10^{-7}t^3$ kJ/(kg·°C).

For the calculation, a 3D model of an electrode with the following dimensions was built [14]: length, 1.8 m; electrode diameter, 0.45 m; the diameter of the hollow channel in the electrode, 0.09 m.

The next stage of our work was the generating of the computational mesh on GHE; it consisted of 16,434 elements and 72,683 nodes, which made it possible to acquire more accurate information on any part of the electrode's body.

The boundary conditions were set for calculating the non-stationary heat transfer during each period of the out-of-furnace steel processing. For the outer and inner surface of GHE and its lower end we set for all periods the third type boundary conditions, and for the upper end – the second type boundary conditions. Heat exchange parameters were calculated according to the procedure given in [7]. At each subsequent period, the temperature field of GHE, acquired at the end of the preceding period, was taken into consideration.

According to the concept of the non-stationary transmission of heat by convection [12], it is associated with the process of gas movement and occurs the more intense, the faster and more often the volume of gas would reach the heating or cooling surface. However, not only the process of movement but also the physical nature of gases, the shape and size of a solid contribute to the heat output by convection.

Heat transfer by convection is a very complex process that depends on the conditions of movement, conditions of gas flow around solids of different geometric shapes and sizes, as well as the phenomenon of thermal conductivity.

The laminar one-dimensional flow has no transverse movements of macro volumes of gas. Therefore, convection heat transfer from the stream to the surface of the solid is absent. In this case, the transfer of heat inside the flow is carried out by thermal conductivity, which is confirmed by experience.

The mode of gas movement in a GHE channel is characterized by the Reynolds number:

$$\mathrm{Re}=\frac{wd}{v}=\frac{0.00524\cdot0.09}{0.000013}=36, \qquad (2)$$

where w is the average flow rate of gas, m/s; d is the diameter of GHE inner channel, m; v is the coefficient of gas kinematic viscosity, m^2/s.

It is determined that for the specified conditions the gas moves under a laminar mode, so the calculation of the coefficient of convective heat transfer inside the channel is carried out for the forced convection under a laminar mode from the Nusselt number.

Nusselt number was calculated from the following formula:

$$\overline{Nu_f}=0.15\,\mathrm{Re}_f^{0.33}\,\mathrm{Pr}_f^{0.43}\,\mathrm{Gr}_f^{0.1}\left(\frac{\mathrm{Pr}_f}{\mathrm{Pr}_w}\right)^{0.25}\bar{\varepsilon}_l, \qquad (3)$$

where $\bar{\varepsilon}_l$ is the coefficient that takes into consideration a change in the heat output along the GHE channel [12]; Pr_w is the Prandtl number for the wall (index «w»); Pr_f – for a gas flow (index «f»), which is determined from the following formula:

$$\mathrm{Pr}=\frac{v}{a}. \qquad (4)$$

where a is the coefficient of thermal diffusivity, m^2/s.

The Grashof number was calculated from the following formula:

$$\mathrm{Gr}=\frac{g\beta d^3\left(T_{f.avg}-T_w\right)}{v^2}, \qquad (5)$$

where g=9.81 m/s^2 is the gravitational acceleration; $(T_{f.avg}-T_w)$ is the temperature difference between the gas and surface, K;

$$\beta=-\frac{1}{\rho}\left(\frac{d\rho}{dT}\right)_{P=\mathrm{const}}$$

is the coefficient of thermal expansion of gases, K^{-1}.

Convection heat transfer is carried out under conditions of the joint progress of convective and conductive heat transfer processes. According to Prandtl's theory, a thin boundary layer occurs in any stream in close proximity to the surface of the solid. Through the laminar boundary sublayer, heat is transmitted by thermal conductivity, and heat is supplied to it by convection.

Heat exchange between the surface of the side walls of the electrode and the atmosphere inside LF occurs due to free convection and radiation. We determined a convection heat transfer coefficient by free convection [12] in the change range of $\mathrm{Gr}_f\cdot\mathrm{Pr}_f>10$ (corresponding to the turbulent movement of the medium) for the outer surface of vertically installed GHE from the following formula:

$$\overline{Nu}=0.15\left(\mathrm{Gr}_f\cdot\mathrm{Pr}_f\right)^{\frac{1}{3}}\cdot\left(\frac{\mathrm{Pr}_f}{\mathrm{Pr}_w}\right)^{\frac{1}{4}}. \qquad (6)$$

The average heat transfer coefficient for the lower end of the graphitized hollow electrode during periods without heating [12] is:

$$\bar{\alpha}=A\sqrt[4]{t_w-t_f},\ \mathrm{W/(m^2\cdot°C)}, \qquad (7)$$

where A=1.63 coefficient for the horizontal surfaces facing downwards; t_w and t_f is the temperature, respectively, of the surface and environment at a distance from the surface, °C.

To calculate the heat transfer radiation under the boundary conditions, the emissivity factor of graphite was taken to be equal to 0.71 [13].

At the last stage, the following calculation parameters were set: the time of each period in accordance with Table 1, while the calculation step, the minimum and maximum duration of the step were assigned automatically based on the duration of the period). For the GHE upper end, the second type boundary conditions were chosen: the heat flux density, 0 W/m^2, which corresponds to the absence of heat transfer through it. And for the rest of the surfaces, we set third type boundary conditions. Temperature conditions of the medium under the LF lid were adopted in accordance with well-known practices of its operation [14].

When calculating the GHE temperature field, the Joule heat output was taken into consideration when passing an alternating electric current throughout the GHE volume, whose value was calculated from the following formula [13]:

$$q_v = \frac{16 \cdot I^2 \rho}{\pi^2 \left(D_{out}^2 - D_{in}^2\right)^2}, \text{ MW/m}^3 \quad (8)$$

where ρ is the specific electrical resistance of electrode material, Ohm·m; I is the arc current (for a three-phase alternating current, the actual current value), A; D_{out} and D_{in} is the diameter of the outer and inner GHE surface, m.

In periods I and III, the main part of the heat from arc burning is transmitted to the lower end of the electrode by radiation.

Given the high burning temperature of the arc, the proportion of convective heat transfer is quite small; it was neglected. Since periods II and IV do not imply gas injection to the GHE channel, the heat transfer is absent because the surface temperature of the channel and the gas in it are the same.

5. Results of studying changes in the temperature field of a graphitized hollow electrode during metal processing periods

5. 1. Calculating the values of Joule heat generation and heat transfer coefficients

To acquire data on the changes in the temperature field of the graphitized hollow electrode, we calculated the main thermophysical indicators of the electrode operation process during metal processing in ladle-furnace.

The calculated value of generating the Joule heat for the first processing period was 1.11 MW/m^3; for the third – 1.15 MW/m^3. Table 1 gives the values of heat transfer coefficients in W/(m^2·°C) for the accepted periods of metal processing.

The results of the calculation of heat transfer coefficients are consistent with the data reported in [14] regarding their value under conditions of natural and forced convection in the gas environment.

Table 1

Convection heat transfer coefficients, W/(m^2·°C)

Region	Period			
	I (6 min)	II (4 min)	III (10 min)	IV (25 min)
GHE outer surface	5	3.7	3.4	17
GHE inner surface	1.6	–	1.8	–
GHE bottom end	–	11	–	13

5. 2. Determining the temperature field of the graphitized hollow electrode at different periods of operation

Based on the results from numerical modeling, we acquired data on the main temperature characteristics of GHE. The overall pattern of temperature changes during heating periods (I and III) and holding periods (II and IV) is shown in Fig. 1.

Fig. 2 shows the temperature field of a GHE 3D model during each period of steel processing in ladle-furnace.

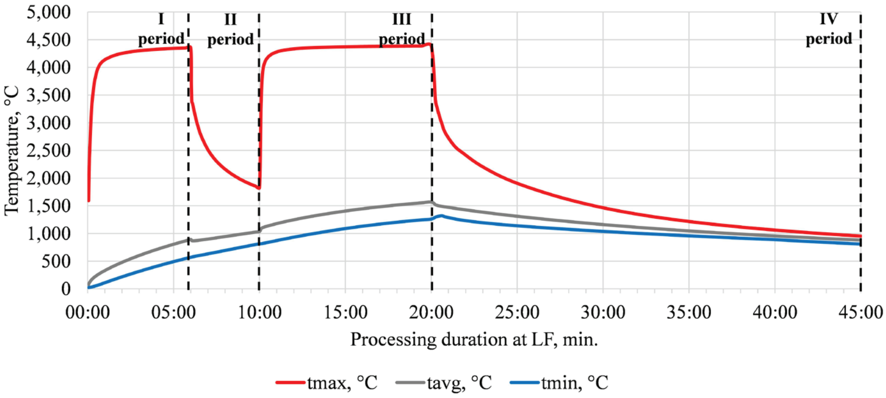


Fig. 1. Changes in the temperature throughout the GHE volume at different periods of steel processing at LF

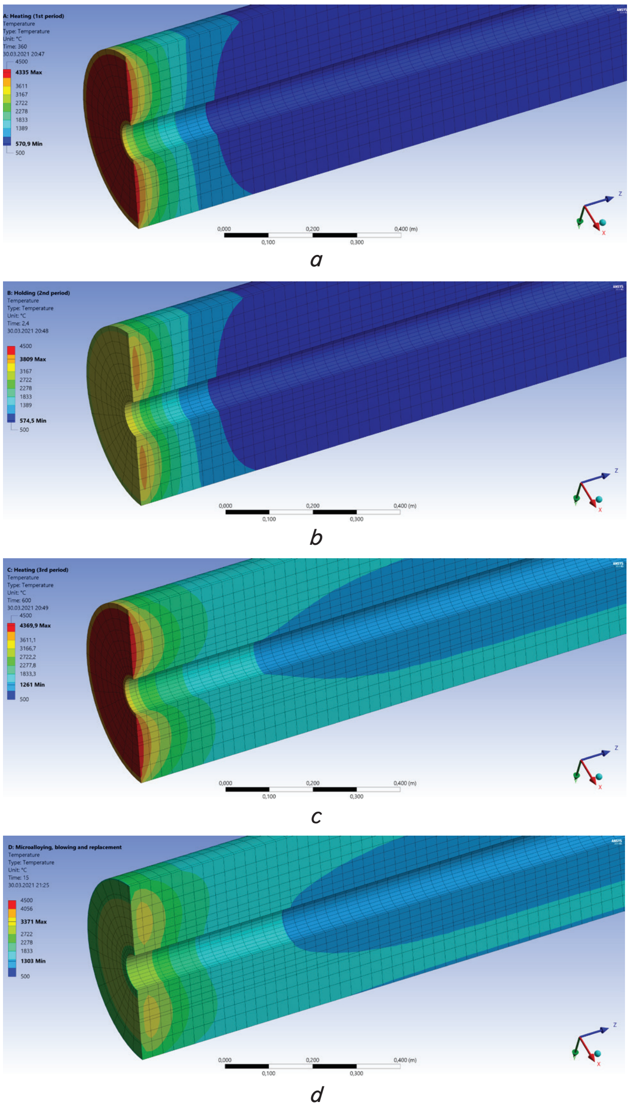
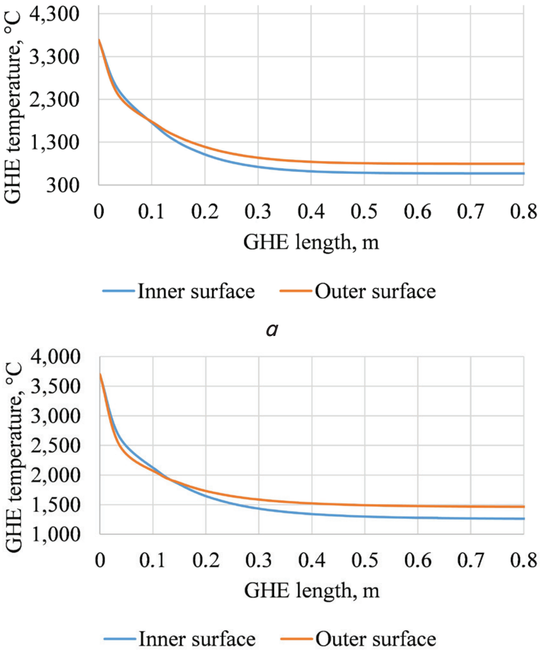


Fig. 2. The cross-section of GHE model during periods I, II, III, and IV in the out-of-furnace steel processing: *a* — period I; *b* — period II; *c* — period III; *d* — period IV

Data on the changes in temperature along the length of the electrode on the outer and inner surfaces at the end of metal heating periods in ladle-furnace are shown in Fig. 3.

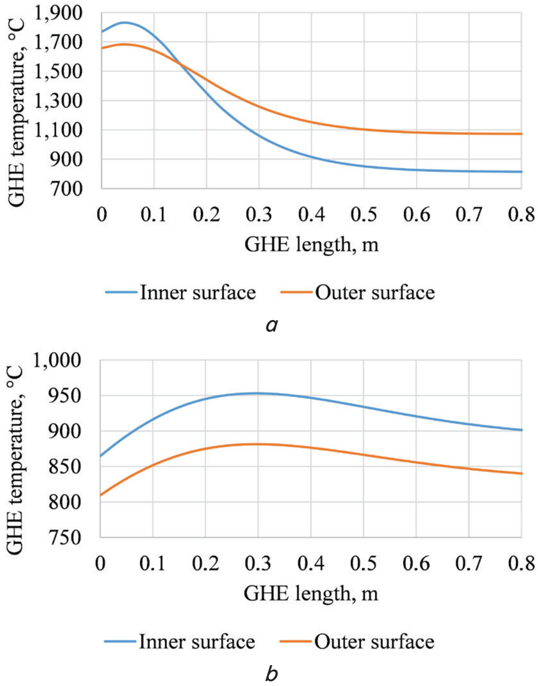


a

b

Fig. 3. Change in temperature on the outer and inner surface of GHE by its length during steel processing periods: *a* — period I; *b* — period III

Fig. 4 shows the values of changes in the surface temperature of the hollow electrode without electricity and neutral gas supply.



a

b

Fig. 4. Changes in temperature on the outer and inner surface of GHE by its length at the end of: *a* — period II; *b* — period IV

The data acquired on temperature values of both the side surface of the electrode and its inner surface testify to the rather complex nature of the formation of heating and cooling zones, especially when switching from one mode to another. In addition, we can note the tendency of minor changes in the thermophysical characteristics of the electrode in the established region from the bottom of the electrode. The supply of neutral gas through the hole in the electrode somewhat improves the cooling of only the inner part of the electrode and during periods without power supply.

6. Discussion of results of studying changes in the temperature field of the graphitized hollow electrode

The results of our study convincingly indicate quite significant changes in the temperature field of the electrode, depending on the periods of operation and supply of neutral gas.

Since the increase in the minimum temperature is almost linear, we can conclude that the areas of the electrode far removed from the arc are heated mainly due to Joule heat. The same applies to the average mass temperature. The maximum temperature values of GHE are observed in the lower end of the electrode since the heat source of this part is the electric arc (Fig. 2). A sharp increase in the maximum electrode temperature values, observed at the beginning of heating periods I and III, is a consequence of a large difference in the temperature of the arc and the end of the electrode; in the further process of heating the electrode, it slows down.

The opposite pattern is observed in periods II and IV after the cessation of heating of the metal (Fig. 1). The high temperature difference between the external environment and the lower end of the electrode contributes to the rapid cooling of the latter. An additional effect on the rapid cooling of the electrode is exerted by a high temperature gradient along its length. Due to the rapid cooling of the end of the electrode, the temperature difference between it and the environment decreases, slowing down its cooling.

It was established that during heating periods (Fig. 3), a significant gradient of temperatures along the length of the electrode is noted, which is observed only at the interval of 0.35 m from the lower end. The temperature gradient value for the first period reached 8,286 °C/m, for the third period – 6,571 °C/m, then temperature values are distributed relatively evenly along the entire length of the electrode. The difference in absolute temperature values in these periods is explained by the heat accumulation process obtained by the electrode in the first period.

It is determined that in periods II and IV, which are characterized by cooling of the electrode, the locally overheated zones are formed at a distance of 0.03–0.08 m from the GHE lower end. It was established that the locally overheated zone takes the shape of a torus flattened along the axis, as shown in Fig. 2, *b*, *d*. The calculated temperature gradient in the horizontal plane from the epicenter of the torus is: to the inner surface – 379 °C/m; to the outer surface – 3,613 °C/m; and the vertical plane to the end of the electrode – 1,469 °C/m.

The difference in absolute temperature values in periods II and IV is explained by the duration of these periods, and the conditions under which the GHE is. In period IV, a ladle is replaced; during this operation, the electrodes, for a long time, are outside the atmospheric zone of ladle-furnace, which leads to a more uniform distribution of heat throughout the GHE volume.

The data that we acquired on the values of the temperature field of the graphitized electrode during its operation make it possible to calculate expedient modes of supplying a mixture of gases through the electrode channel during different periods of the out-of-furnace processing. The gas supply would reduce the temperature load on the electrode; note that works [6, 7] report data on the results of gas supply without determining their effect on the heating process of the electrode itself.

Based on our numerical modeling, new data have been obtained about the formation of a locally overheated zone in the lower part of the electrode. We have determined the parameters of this zone and demonstrated the influence of temperature distribution during electrode operation without electric loading, which occurs during steel processing in ladle-furnace. That is in contrast with works [8, 9] that report the results of electrode operation under the mode of electric arc constant burning, which does not fully meet the conditions of metal processing in ladle-furnace.

The GHE temperature field may differ slightly when the size of the electrode changes, the different duration of each processing period, and their quantity, as well as the power of the transformer. In particular, reducing or increasing the size of the electrode could not affect the distribution of temperature but would change its value, especially at the surface of the channel. Instead, changing the processing duration affects the distribution of temperature and its value at the end of each period. The power of the transformer affects the burning temperature of the arc and the amount of Joule heat, which could affect the average mass temperature, heating speed, and the overall temperature field of the graphitized hollow electrode.

Changing the flow rate of gas and its type would not significantly affect the temperature field of GHE since, under the conditions of processing, low consumption of any gas would provide for a stable laminar flow. That would ensure an almost unchanged value of the convection heat transfer coefficient.

One of the options for the use of GHE is the supply of bulk materials through the channel for steel processing (deoxidation, alloying, desulfurization, micro-alloying). Our analysis has determined the temperature conditions in the electrode channel, which make it possible to calculate the heating of bulk materials of various compositions with different properties moving through this channel. It is also possible to determine the optimal fraction of bulk materials for unhindered movement along a GHE channel, thereby enabling rapid heating and assimilation of them with metal.

The data reported here would make it possible in the future to calculate and optimize material costs and gas consumption to regulate the oxidation of metal and slag; reduce the chemical effect on the electrode, especially in the high temperature zone by using a mixture of gases supplied by a hollow electrode.

The conditions for applying the results of this study are within the framework of steel processing in ladle-furnace involving ladles with a capacity of 150–250 tons. Promising directions for the further advancement of our study may be to devise the newest technologies to inject a mixture of gases and powdered materials into the metal, thereby extending the life of electrodes, and improving the burning conditions of the arc.

7. Conclusions

1. Based on our study results, the value of Joule heat generation was derived when an electric current passes through a graphitized hollow electrode during heating periods. Thus, the values of the heat generation for the first and third periods were, respectively, 1.11 MW/m^3; 1.15 MW/m^3; we also determined the proportion of Joule heat generation in the overall thermal balance of electrode heating, which amounted to 23.6 % in the first period, and 14.1 % in the third.

The convection heat transfer coefficients were calculated for different operating conditions of the electrode; it is shown that this indicator can vary significantly. The difference in the values of heat transfer coefficients for the inner surface of the electrode channel is 1.9–3.1 times less than for the side surface and almost 10 times less than the end part.

2. The values of changes in the temperature field along the entire length of the electrode at the outer and inner surfaces have been established for each period. It is determined that during the periods of electrode operation with a current supply there are significant values of the temperature gradient in the end part, which reached 8,286 °C/m. It has been established that during periods of operation without a current supply, the formation of a locally overheated zone in the lower part of the electrode is observed, which takes the shape of a torus flattened along the axis, formed as a result of the accumulation of heat from the preceding period.

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