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INVESTIGATING CAVITY FORMATION IN AN ELECTRIC ARC ZONE DURING OUT-OF-FURNACE PROCESSING OF STEEL

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The object of this study is the interaction zone between a graphitized hollow electrode (GHE) and a metal bath on the «ladle-furnace» installation.

The regularities of the formation of the geometric parameters of the hole were established for the purpose of further evaluation of the heat exchange under the electrode in the arc combustion zone under different operating conditions of the «ladle-furnace» installation.

An experimental methodology was devised, and a laboratory setup was built for physical simulation on a cold model. The values of the geometric parameters of the cavity formed by the electric arc discharge in the sub-electrode zone were calculated. In particular, the area of the curved surface of the cavity is about 0.2 m^2 at a depth of 40 mm. The regularities of formation of the geometry of the cavity during gas injection through the GHE channel have been established, in particular with regard to the area and depth of the cavity. Thus, with a gas consumption of 3–20 m^3/h and a slag cover height of 100 mm, the area reaches 0.28–0.5 m^2, while the depth of the cavity ranged from 5 cm to 19 cm, respectively. Rational flow rates of gas supplied through the channel of the graphitized hollow electrode were established, which for a slag cover of 100 mm are 3–6 m^3/h and for a slag cover of 200 mm – 6–10 m^3/h.

The peculiarities of the formation of a metal cavity in the sub-electrode zone under the conditions of gas supply through the channel of a graphitized hollow electrode during out-of-furnace processing of steel at the «ladle-furnace» installation were investigated.

The patterns of the formation of the geometry of the cavity in the arc combustion zone, which were obtained using cold modeling, could subsequently make it possible to perform calculations of heat transfer from the electric arc discharge to the metal bath. That will also make it possible to determine the share of heat absorbed by slag and metal under the conditions of using a conventional electrode, and a hollow one with gas supply through its channel during out-of-furnace processing of steel at the «ladle-furnace» installation

Keywords: physical modeling, «ladle-furnace» installation, graphitized hollow electrode, geometric parameters of the cavity

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1. Introduction

The development of modern steel production typically includes the improvement of technologies and optimization of processes, which leads to improved productivity and quality of manufactured products. One of the priority vectors of development is non-furnace processing of steel at the «ladle-furnace» (LF) installation.

During steel processing at LF, the following operations are carried out: desulfurization, alloying, modification, and removal of non-metallic inclusions. Carrying out these operations is accompanied by the consumption of a large amount of heat, which is compensated by heating the metal bath with an electric arc discharge formed by graphite electrodes (GEs). During the operation of the electric arc device, an electric arc is formed between the lower end of the electrode immersed in the slag and the surface of the metal bath, which in turn forms a cavity in the shape of a «meniscus» on the surface of the metal.

Research on the use of a graphitized hollow electrode (GHE) during steel processing at LF will make it possible to evaluate the effectiveness of the gas supply through its channel on the change in the geometric parameters of the cavity formed in the arc burning zone. Currently, there are practically no reliable data on the parameters of the formation of a metal cavity under the influence of an electric arc and gas supply through the GHE channel in the sub-electrode zone. Also, there are no data on the limit consumption of gas supplied by the GPE channel, and the impact of excess consumption.

Based on this, an urgent task is to study the effect of gas supply through the channel of the graphitized hollow electrode on changes in the geometric parameters of the metal cavity during the processing of steel at LF. In the future, this will make it possible to evaluate the efficiency of heat transfer through the surface of the cavity.

2. Literature review and problem statement

The authors of works [1, 2] analyzed the use of a graphitized hollow electrode (GHE) in metal processing on a «ladle-furnace» installation. The analysis revealed that the GHE operation with gas supply through its opening has a positive effect on processing parameters such as heat balance, electrode wear, metal desulfurization indicators and, to some extent, on mass transfer processes.

Out-of-furnace processing of steel makes it possible to reduce the content of non-metallic inclusions (NMI) due to the organization of improved mass exchange conditions. Depending on the assortment of steel, there are caveats regarding the content of NMI [3]. Despite the small volume, such inclusions can negatively affect the properties of steel [4, 5]. Processing at the LF involves refining, deoxidation, alloying, and modification [6, 7]. At this stage of the development of non-furnace steel processing technologies, metal purging with inert gas in a steel ladle through bottom purging units is used, which ensures the specified mass transfer rates between metal and slag [8, 9].

The method of blowing metal with neutral gas into the ladle «from above» through a vertically immersed nozzle is also used. Injecting an inert gas (typically argon) into the molten steel in a ladle is more accessible but the indicators of metal refining do not fully ensure the achievement of equilibrium [10].

The authors of works [11, 12] indicated that increasing the intensity of blowing through the bottom blowing units can lead to the process of breaking the slag cover in the steel ladle under the action of rising gas-metal emulsion flows. This can lead to a deterioration of metal heating conditions at LF while the efficiency of refining increases with an increase in gas consumption. The authors of work [13] presented data on the effect of the location of the bottom blowing devices on the rupture of the slag layer in the steel ladle.

Technological operations of out-of-furnace metal processing are associated with heat losses, and for their compensation, an energy source is needed, which is an electric arc built with the help of graphite electrodes (GEs).

To ensure the stable existence of an electric discharge above the surface of a liquid metal bath, the presence of a gaseous medium is necessary [14]. The use of a graphitized hollow electrode during metal processing at LFI has shown a positive effect on the formation and existence of an electric discharge, improvement of metal desulfurization conditions, reduction of processing time, and reduction of electrode costs [15, 16].

An analytical review of the above studies [1–16] indicates the influence of gas-dynamic indicators of metal blowing on the formation of a gas-metal emulsion in the deep volumes of a steel teeming ladle and on the indicators of mass transfer. However, currently there are no data on the formation of the zone of interaction of the gas jet with the metal under the slag layer during blowing through a graphitized hollow electrode with various amounts of slag. Therefore, it is expedient to conduct a study to determine the rational parameters of neutral gas consumption through a hollow electrode. This could ensure stable burning of the electric arc; impossibility of breaking the slag layer around the electrode by upward gas flows; improving the conditions of heat transfer to the metal melt during processing at the ladle-furnace installation.

3. The aim and objectives of the study

The purpose of this study is to evaluate the impact of gas injection through the GHE channel during steel processing at the «ladle-furnace» installation at different gas flow rates and slag cover thickness on the formation and change of the geometric parameters of the cavity. This will make it possible to increase the efficiency of steel heating in the ladle by increasing the heat transfer from the arc to the metal surface.

To achieve the goal, the following tasks were set:

– to determine the geometric parameters of the cavity formed under the action of an electric arc without gas supply through the channel of the graphitized hollow electrode;

– to determine the impulse of the jet, which is equivalent to the impulse of the electric arc during steel processing on the «ladle-furnace» installation;

– to determine the geometric parameters of the metal cavity and the rational flow of gas through the channel of the graphitized hollow electrode during out-of-furnace processing.

4. The study materials and methods

The object of our research is the zone of interaction between the graphitized hollow electrode (GHE) and the metal bath of the «ladle-furnace» installation.

Increasing the intensity of gas injection to a certain limit will help increase the surface area of the metal cavity, which will improve heat transfer.

Physical modeling was carried out under isothermal conditions, i.e., the influence of thermal processes on the hydrodynamics of the bath was neglected.

The efficiency of thermal processes in the furnace and liquid bath is determined by the properties of the electric arc. The effect of the electrodynamic field provides an increase in heat transfer from the arc to the liquid bath, which helps speed up metallurgical processes and metal mixing. Also, the degree of operation of LF transformer exerts its influence; when it increases, the voltage and current increase accordingly, thereby increasing the length of the arc. Under the electromagnetic action, the slag moves to the sides from under the arc burning zone and sinks into the metal. The arc sinks to a depth where the force is balanced by the hydrostatic pressure of the melt. In practice, it is impossible to determine the shape of the cavity formed under the influence of an electric arc in the sub-electrode area visually or by photography. The most likely shape of a cavity formed under the action of an electric arc at the point of contact with a metal bath is a spherical segment, «meniscus» [1].

In this regard, there is a need to calculate the geometric parameters of the cavity formed under the action of an electric arc without gas supply, during an out-of-furnace processing of steel at LF. To calculate the parameters of the cavity, the depth of the cavity and its radius are calculated in the beginning.

During research into the depth of arc penetration in furnaces with a volume of 100 and 200 tons, experimental data were obtained, which showed that the magnitude of the arc for these furnaces is 3 mm/kA, while the height of the meniscus of the metal formed under the action of an electric arc is determined using the following formula [1]:

$$h_{men} = 3 \cdot 10^{-3} \cdot I_A, \text{ m}, \quad (1)$$

where I_A is the arc current strength, kA.

The radius of the circle at the base of the cavity, which has the shape of a meniscus, can be determined as follows [2]:

$$r_c = r_e + L_A \cdot \sin\theta, \text{ m}, \quad (2)$$

where r_e is the radius of the electrode, m; θ is the angle of inclination of the arc pole to the axis of the electrode; L_A is the length of the arc, m.

To calculate the radius, it is necessary to first determine the length of the arc, which, according to various researchers, can be determined using different formulas. Calculating the length of the arc is very complicated, therefore the «Danieli» company provides an empirical formula for calculating the length of the arc for furnaces of its design [3]:

$$L_A = U_{ph} - 35, \text{ mm}, \quad (3)$$

where U_{ph} is the phase voltage on the electrode, V.

For DSP AT «OEMK» with a capacity of 150 t, work [4] proposes to calculate the length of the arc according to the following formula:

$$L_A = \frac{U_A - U_{a-c}}{\beta_U}, \text{ m}, \quad (4)$$

where U_A is the arc voltage, V; U_{a-c} is the anodic-cathode voltage drop, which was taken as U_{a-c}=30 V for the conditions of melting electrical steel in EAF; where β_U is the voltage gradient in the arc column (depending on the melting period, β_U=500–1000 V/m).

Since the value of the length of the arc is required to find the radius, this parameter can be determined using the following formula [5]:

$$L_A = \frac{U_A - a}{b} \cdot 10^{-3}, \text{ m}, \quad (5)$$

where a is the sum of cathodic and anodic voltage drop; according to various researchers, it is 17 V [1] and 22 V [5]; b is the potential gradient in the arc column b=1.0 V/mm, for the end of steel melting, b=0.8 V/mm for the oxidation and reduction periods [1, 5].

According to the technological instructions of most plants based on the operation data of LF, the authors of works [5, 6] experimentally determined the value of this parameter to be 102.7–116.7 V. At the same time, the recommended current strength of the electrodes was 26.2–39.5 kA.

A comparison of the results of calculating the length of the arc according to formulas (3) to (5) is given in Table 1.

Table 1

Arc length comparison

Source	[3]	[4]	[5]	[6]
Arc length, mm	82	145	95	73
Diameter of the base of the cavity, mm	226	228	227	226

The result obtained according to the formula from paper [4] is the largest of those presented and is intended for calculation under the conditions of steel melting in EAF. The length of the arc, obtained according to data from studies [3, 6], corresponds to the values during out-of-furnace processing, but has a narrow range of application as it is calculated only for LFs of the company «Danieli» (Italy), which, for example, are used at the plant of PrAT «Dniprospetsstal» (Ukraine). Considering the above, we consider the result of 95 mm, obtained according to the data from work [5], to be the most rational.

The study into the influence of the intensity of gas supply by a graphitized hollow electrode on the formation of a cavity on the metal surface was carried out by the method of physical modeling.

The key task in finding similarity criteria for physical modeling is the selection of the most significant parameters that affect the process under study. Taking into account all parameters of the process in the model does not make it possible to simulate it because it will make it impossible to choose model substances and the scale of the model.

The main requirement when carrying-out physical modeling is to observe the most complete similarity of the processes on the prototype and model. According to the theorem of similarity, it is possible to ensure similarity only if the determining criteria of similarity are equal on the sample and the model. Therefore, defining criteria is one of the most important tasks of experiment preparation.

At the second stage, based on the analysis of the process and logical considerations, a set of independent physical quantities is formed that characterize the physical system of the modeling object. Using the reference literature, the dimensionalities of all factors are determined, which are then reduced to the main SI units (Table 2).

Table 2

Similarity criteria

Quantity	Units of measure	Scale	Dimensionless quantity
i	kg·m/s^2	–	$I = \frac{i}{\rho_{st} \cdot g \cdot d_{ch}^3}$
d_k	M	m	–
Δ_{sl}	M	–	$\Delta_{sl} = \frac{\delta_{sl}}{d_{ch}}$
H	M	–	$H = \frac{h}{d_{ch}}$
g	m/s^2	s	–
ρ_{st}	kg/m^3	kg	–
ρ_{sl}	kg/m^3	–	$P_{sl} = \frac{\rho_{sl}}{\rho_{st}}$
σ	kg/s^2	–	$Bo = \frac{g \cdot (\rho_{st} - \rho_{sl}) \cdot d_{ch}^2}{\sigma}$

Since during «water» modeling it is impossible to directly reproduce the effect of an electric arc on a metal bath, it was assumed that the pulse of the gas jet on the model imitates the total pulse of the argon jet and the electric arc on the prototype. In this case, the magnitude of the impulse of the equivalent effect of the arc can be found by comparing the depth of the cavity determined by formula (1) with the value obtained from the results of physical modeling.

Based on logical considerations, we assume that the process of formation of a cavity and rupture of the slag layer is influenced by the following parameters: i – pulse of the gas jet; d_{ch} is the diameter of the electrode channel; Δ_{sl} is the thickness of the slag.

In [17], it was proposed to use the criteria of the dimensionless criterion π for the physical simulation of blowing steel from above with an inert gas. However, in these studies, blowing was carried out with a lance submerged in the metal, so the results obtained by the authors cannot be used to describe the geometry of the cavity formed by blowing through the hollow electrode. In other studies [18–20], the authors used the Archimedes criterion to model the top blowing of steel in the converter. However, the intensity of oxygen supply in the converter is disproportionately large, which also does not allow using the mathematical models obtained in those studies to calculate the dimensions of the cavity under these conditions.

At the third stage, based on the calculated similarity criteria, an experiment plan was developed, which is given in Table 3.

The mathematical model of the process in criterion form is always a power function of the form:

$$\pi_1 = A \cdot \pi_2^n \cdot \pi_3^m, \quad (6)$$

where π_1, π_2, π_3 are similarity criteria; A, n, m are regression coefficients of the power function.

Accordingly, each of the criteria must be varied at three levels: lower, zero, and upper. To determine the regression coefficients of a power function, it is necessary to convert it to a linear form by logarithmization. Thus, taking into account this transition, the value of the zero level of each factor was determined by the following formula:

$$\pi_0 = 10^{\frac{\lg \pi_{\min} + \lg \pi_{\max}}{2}}, \quad (7)$$

where π_{min} and π_{max} are the minimum and maximum value of the criterion, respectively.

Table 3

Experiment plan

No.	Dimensionless criteria		Corresponding parameters	
	slag thickness	pulse	Δ_{sl}, mm	gas consumption, m^3/h
1	–	–	6	0.13
2	–	0	6	0.25
3	–	+	6	0.5
4	0	–	9	0.13
5	0	0	9	0.25
6	0	+	9	0.5
7	+	–	14	0.13
8	+	0	14	0.25
9	+	+	14	0.5

At the fourth stage, an experimental facility for cold «water» was built to determine the effect of the gas jet pulse when using GHE on the formation of a cavity, taking into account the action of an electric arc. The scheme of the facility is shown in Fig. 1.

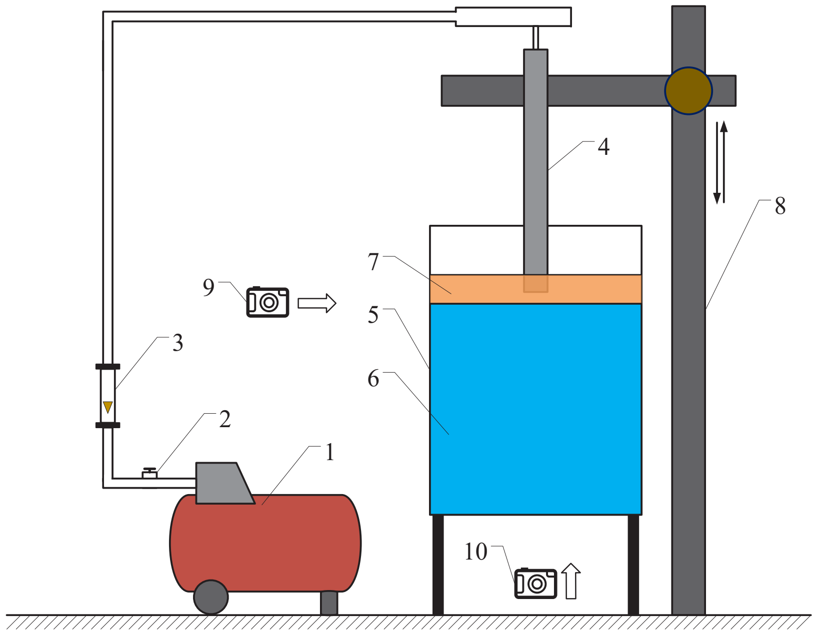


Fig. 1. Scheme of the experimental facility:
1 — compressor; 2 — reducer; 3 — rotameter; 4 — graphitized hollow electrode; 5 — glass flask; 6, 7 — model liquid; 8 — tripod; 9, 10 — frontal and bottom video cameras, respectively

The gas was supplied by compressor 1 through reducer 2, which regulated the volume flow rate. To determine the volume flow rate of gas, we used rotameter 3 (RM 2.5 GUZ). Gas was injected through tube 4, which imitated a graphitized hollow electrode; its height was adjusted using tripod 8. A glass flask 5 was used as a scale model of a ladle; water 6 was used as a liquid imitating liquid metal; for a liquid that imitates slag – sunflower oil 7. The video recording took place from the front at the metal-slag boundary with the help of camera 9, and from below with the help of camera 10.

The experiments were carried out with changes in the thickness of the slag layer, the height of the location of GHE above the level of the metal mirror, and the modes of gas supply to the electrode. The thickness of the slag ranges from 6 mm to 14 mm, which corresponds to the thickness of the slag on the prototype from 100 to 200 mm. The height of the GHE above the level of the metal mirror is equal to 70 % of the thickness of the slag. The modes of gas supply by the electrode varied within 0.13–0.5 m^3/h, which corresponds to the gas consumption on the prototype from 3 to 20 m^3/h. The following parameters were controlled: gas pressure, height of the graphitized hollow electrode, slag thickness, depth of the formed cavity.

5. Results of studying changes in the geometric parameters of the metal cavity during gas supply through the channel of the graphitized hollow electrode

5. 1. Results of determining the geometric parameters of the cavity

The resulting video files were edited and analyzed using the Adobe Photoshop software. Fig. 2 shows the view of the bath model when blown by a graphitized hollow electrode with a gas flow rate of 0.13 m^3/h, a slag thickness of 6 mm, which is 3 m^3/h and 100 mm on the prototype, respectively.

Fig. 3 shows blowing on a model with a gas flow rate of 0.5 m^3/h, a slag thickness of 6 mm, which is 20 m^3/h and 100 mm on the prototype, respectively.

Fig. 4, 5 show the view of the bath model when blowing with a graphitized hollow electrode, with a minimum gas flow rate of 0.13 m^3/h and a maximum of 0.5 m^3/h and with a maximum slag thickness of 14 mm. These values correspond to gas flow rates of 3 and 20 m^3/h on the prototype and a slag thickness of 200 mm on the prototype.

The obtained frames made it possible to evaluate the behavior of the slag layer (sunflower oil) and the metal bath (water) during gas injection through the GHE channel during out-of-furnace processing of steel at LF under different operating conditions of the unit.

5. 2. Determination of the pulse of a jet, which is equivalent to the pulse of an electric arc

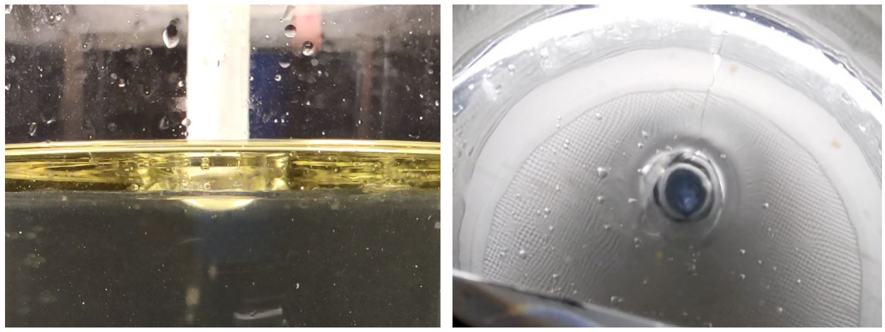
Based on the results of research, data on the dependence of the depth of the metal cavity on the gas consumption and the thickness of the slag layer were obtained and analyzed (Tables 4, 5):

$$H = 6.4 \cdot \frac{I^{0.6}}{\sqrt{\Delta}}, \qquad (8)$$

$$S = 7.3 \cdot I^{0.55} \cdot \Delta^{0.30}. \qquad (9)$$

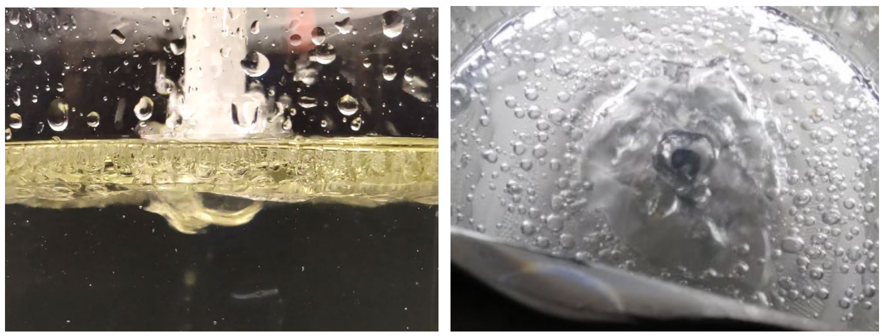
Using formulas (1) to (5), it was established that for the conditions of steel processing at LF with solid graphite electrodes, the depth of the cavity is about 40 mm. Based on this, a dependence plot of the depth of the cavity on the dimensionless pulse and slag height was drawn (Fig. 6). From it, it was determined that the size of the dimensionless impulse of the equivalent impact of an electric arc, depending on the thickness of the slag layer, varies within $(16...28) \cdot 10^{-2}$. The dependence of this parameter on the dimensionless thickness of the slag is determined by the following equation:

$$I = 1.47 \cdot 10^{-2} \cdot \Delta^{1.3}. \qquad (10)$$



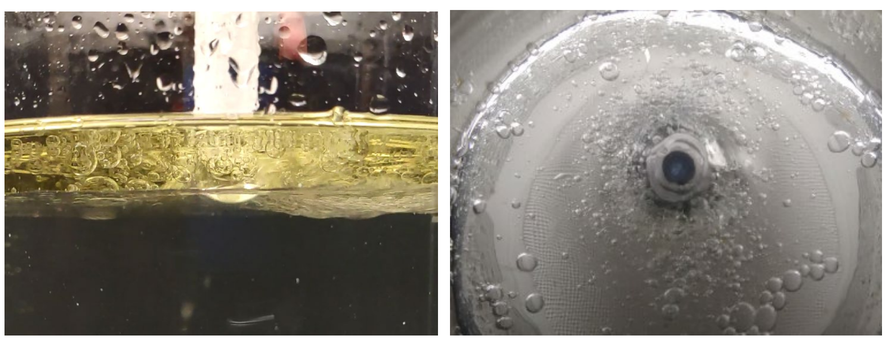
a *b*

Fig. 2. Blowing through a graphitized hollow electrode model with a volumetric gas flow rate of 0.13 m^3/h at an oil height of 6 mm: *a* – side view; *b* – bottom view



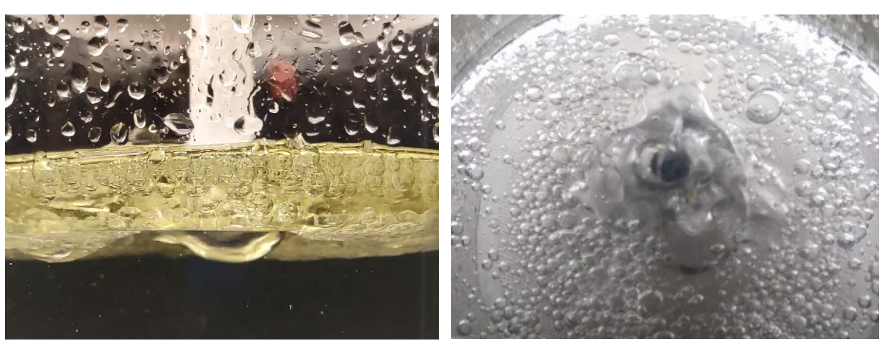
a *b*

Fig. 3. Blowing through a model of a graphitized hollow electrode with a volumetric gas flow rate of 0.5 m^3/h at a slag thickness of 6 mm: *a* – side view; *b* – bottom view



a *b*

Fig. 4. Blowing through a model of a graphitized hollow electrode with a volumetric gas flow rate of 0.13 m^3/h at a slag thickness of 14 mm: *a* – side view; *b* – bottom view



a *b*

Fig. 5. Blowing through a model of a graphitized hollow electrode with a volumetric gas flow rate of 0.5 m^3/h at a slag thickness of 14 mm: *a* – side view; *b* – bottom view

Table 4

Statistical indicators of the mathematical model (8) obtained from the results of regression analysis

Parameter	n	m	A
Regression coefficients	0.6328	–0.5071	6.4272
Standard error	0.0987	0.1057	0.1915
Student's criterion t	6.412	4.796	4.219
The critical value of the Student's criterion t_{cr} (α=0.05)	2.052		
Multiple R	0.9623		
Approximation coefficient R^2	0.9261		
Normalized R^2	0.8965		
Standard error for estimating H	0.0531		
F-observation value (F-statistics)	31.318		
F-probability distribution	0.0015		

Table 5

Statistical indicators of the mathematical model (9) obtained from the results of regression analysis

Parameter	n	m	A
Regression coefficients	0.5527	0.2989	7.2815
Standard error	0.0460	0.0267	0.0388
Student's criterion t	12.023	11.119	22.206
The critical value of the Student's criterion t_{cr} (α=0.05)	2.052		
Multiple R	0.9401		
Approximation coefficient R^2	0.8838		
Normalized R^2	0.8770		
Standard error for estimation S	0.0420		
F-observation value (F-statistics)	129.31		
F-probability distribution	$1.2819\cdot10^{-16}$		

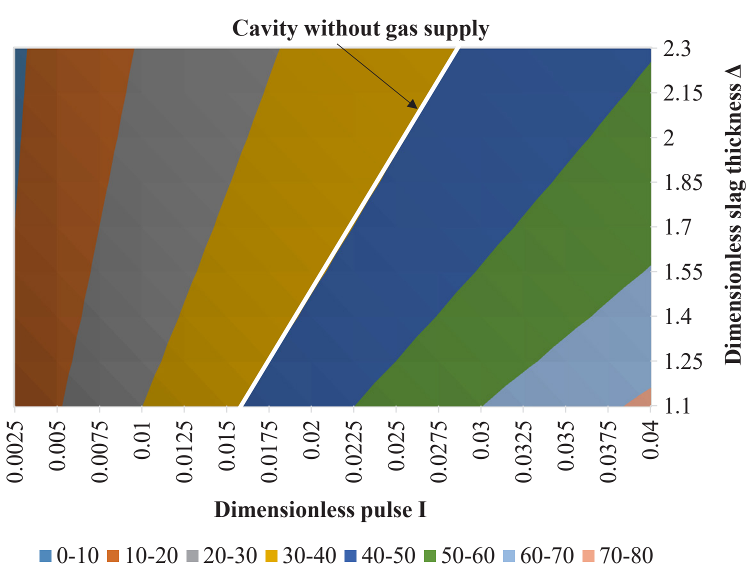


Fig. 6. Dependence of the depth of the cavity on the dimensionless pulse and thickness of the slag

The plot presented in Fig. 6 and equation (10) demonstrate that the limit showing the momentum of the arc is almost linear.

5. 3. Determination of the influence of processing parameters on the formation of the cavity

Taking into account the arc equivalent of models (8) and (9), it should be rewritten as:

$$H = 6.4\cdot\frac{\left(I + 1.47\cdot10^{-2}\Delta^{1.3}\right)^{0.6}}{\sqrt{\Delta}}, \qquad (11)$$

$$S = 7.3\cdot\left(I + 1.47\cdot10^{-2}\Delta^{1.3}\right)^{0.55}\cdot\Delta^{0.30}. \qquad (12)$$

The dependence plot of the area of the metal cavity on gas consumption and the thickness of the slag layer is shown in Fig. 7. After analyzing this plot, we can conclude that without gas supply, the area of the formed cavity with a slag layer thickness of 0.1 m is about 0.19 m^2, and with a slag cover height of 0.2 m – 0.21 m^2. This happens when using both conventional and hollow electrodes and is explained by the fact that a cavity is formed during the operation of the electrode due to the electric arc.

The dependence of the depth of the metal cavity on gas consumption and the thickness of the slag layer is illustrated in Fig. 8.

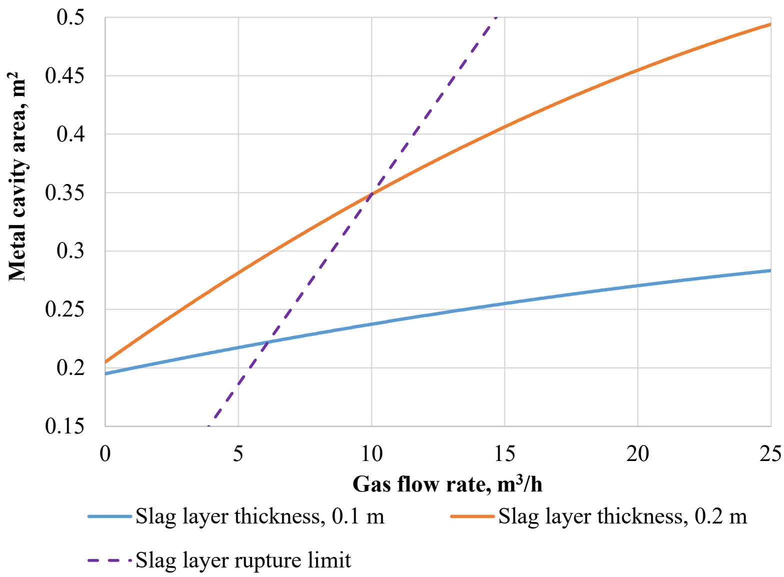


Fig. 7. The dependence of the area of the metal cavity on gas consumption and the thickness of the slag layer

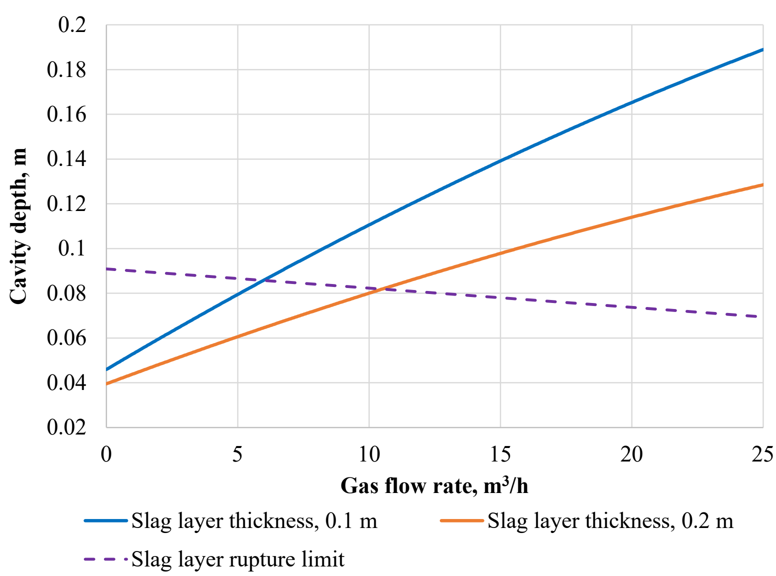


Fig. 8. Dependence of the depth of the metal cavity on gas consumption and the thickness of the slag layer

In this plot, there is an identical relationship with the previous figure. With increasing gas consumption, the depth of the cavity increases.

6. Discussion of research results of changes in the geometric parameters of the metal cavity

The shots shown in Fig. 2 characterize a calm supply of gas without rupture the slag layer around the electrode model, which will have a positive effect on the formation of an electric discharge and the transfer of heat by radiation.

The shots shown in Fig. 3 characterize the rupture of the slag layer around GHE, which has a negative effect on the heat loss from the electric arc into the atmosphere of the LF.

In the frames shown in Fig. 4, at a gas flow rate of 0.13 m^3/h, which is supplied by a graphitized hollow electrode immersed in a slag layer, periodic formation of waves with a small amplitude is observed. While the cavity of the arc combustion zone is closed, the gas does not break the slag layer but diffusely floats up in the form of bubbles. Therefore, these frames illustrate the formation of a calm bath in comparison with the frames shown in Fig. 5, where, in turn, there are wave formations with a larger amplitude of oscillations, disturbance of the slag cover, opening of a cavity in the arc burning zone.

In contrast to the results of previous studies [3–6], where the influence of the arc on the geometry of the cavity was studied exclusively, we studied the influence of the pulse of the gas jet injected through the GHE channel. In particular, it was established that the cavity formed under the electrode in the arc burning zone increases with different intensity during gas supply, depending on the thickness of the slag layer (Fig. 6). The increase in the cavity has a positive effect on the operation of GHE by increasing the contact area of the electric arc with the metal, correspondingly increasing the amount of heat transferred by radiation or heat transfer.

It was determined that for a slag layer with a thickness of 100 mm, the rational consumption of gas supplied by the GHE channel is 3–6 m^3/h, while the area of the cavity is 0.21–0.23 m^2. For a slag layer with a thickness of 200 mm, rational consumption is from 6 to 10 m^3/h, for which the area of the cavity is equal to 0.29–0.35 m^2 (Fig. 7). The proposed rational modes of processing steel at LF complement the already known representations of the processes of forming a metal cavity under the complex influence of an electric arc and a gas pulse. This, in turn, makes it possible to clarify the laws of heat exchange in the sub-electrode zone.

The limitations of the above-mentioned gas consumption are based on the following: at a high intensity of gas injection by a graphitized hollow electrode, the process of rupture the slag layer will occur in the area around the electrode and the cavity will be opened.

This makes it possible to draw slag drops into the metal, which will negatively affect the operation of the electrode. In turn, at the recommended consumption, the gas supplied through the GHE channel floats in a dispersed manner, in the form of bubbles, without breaking the slag, which makes it possible to keep the arc combustion zone in a closed state.

When the gas consumption increases, the depth of the cavity increases for those selected for rational gas consumption, it is from 66 to 85 mm with a slag thickness of 100 mm and 65–82 mm with a slag thickness of 200 mm. This can be seen in the frames shown in Fig. 8. In this case, the cavity is not too deep, the metal bath is in a calm state, the gas moves away from the reaction zone and floats up in the form of bubbles. In the case of an increase in the intensity of gas blowing, the bath is in an unstable state, the slag layer around the arc burning zone opens, and the cavity deepens into the metal bath. This can lead to «clogging» of the cavity with metal melt, which has a negative effect on the operation of power equipment and the graphitized hollow electrode itself during out-of-furnace processing of steel.

It should be emphasized that the purpose of the simulation was to investigate the regularities of the formation of a single cavity. In practice, the heating of the metal is carried out by three electrodes, which leads to the formation of three cavities next to each other, which, due to the agitation of the liquid metal, can affect each other. In addition, a certain influence on the geometry of the cavity can be created by a swarm of bubbles, which are formed when the steel is blown through the bottom porous devices. However, the influence of these factors is minimal and can be studied in the course of further research.

Our models for describing the shape and dimensions of the cavity will make it possible to study the heat exchange in the «plasma-slag-metal» system, taking into account the change in the geometry of the cavity and the formation of additional convection flows due to the gas injection through the GHE channel.

7. Conclusions

1. According to the results of our research, data were obtained regarding the area and depth of the cavity, which is formed in the sub-electrode zone under the influence of the burning of the electric arc and for the studied range of gas consumption. The area of the metal cavity without gas supply through the channel of the graphitized hollow electrode is 0.19–0.21 m^2.

2. It was determined that for the physical modeling of the influence of the intensity of gas injection by GHE on the formation of a metal cavity, it is sufficient to use a dimensionless pulse and linear simplexes. It is these two criteria that make it possible to estimate the impulse of the jet equivalent to the impulse of an electric arc, which, with a dimensionless slag thickness of 1.1–2.3, ranges from 0.016 to 0.0275.

3. The geometrical parameters of the cavity during the gas injection of GHE were determined. In particular, the surface area of the metal cavity during gas supply is 0.28–0.5 m^2, while the depth of the cavity is 5–19 cm, respectively. Rational gas consumption rates for blowing with a graphitized hollow electrode on LF were established, which are 3–6 m^3/h for slag with a thickness of 100 mm and 6–10 m^3/h for slag with a thickness of 200 mm. These limitations are due to the negative consequences of the high intensity of gas blowing through the GHE channel, which lead to heat loss due to the rupture of the slag layer around the electrode. The area of the cavity formed at gas flows that prevent the process of slag rupture around the electrode is determined, with a slag thickness of 100 mm – from 0.21 to 0.23 m^2, with a slag thickness of 200 mm – from 0.29 to 0.35 m^2. An increase in the area of the cavity during the operation of the hollow electrode implies the improvement of heat transfer from the electric discharge directly to the metal.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study and the results reported in this paper.

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Data availability

All data are available in the main text of the manuscript.

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