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The investigation of the thermal performance of the graphitized hollow electrode in the "ladle-furnace" with the supply of neutral gas

The article presents an analysis of heat transfer efficiency from an electric arc discharge formed in the sub-electrode zone to a metal bath under different operating conditions of the "ladle-furnace" (LF). A numerical modeling methodology has been developed, and the obtained data have been analyzed to determine the heat transfer efficiency with the supply of neutral gas through a graphitized hollow electrode (GHE).

The objective of this study *is the numerical modeling of the influence of changing the geometric parameters of the metal bath cavity formed by gas injection through the channel of the graphitized hollow electrode on the heat transfer efficiency from the electric arc to the metal bath at different thickness of the slag cover in the "ladle-furnace".*

Research methods. *Numerical modeling of the heating of the metal bath was performed on a developed 3D model of a steel ladle with liquid metal and a cavity zone formed under the action of an electric arc and gas supplied through the channel of the graphitized hollow electrode. Heating was conducted under different geometric parameters of the cavity and varying heights of the slag cover. The obtained data were analyzed, indicating the advantage of using the graphitized hollow electrode with gas supply through its channel compared to a conventional electrode.*

Results obtained. *The share of heat absorbed by the slag and metal under the conditions of using a conventional electrode and a hollow electrode with gas supply through its channel was determined. The influence of the parameters of the reaction zone formed under the GHE on the heat transfer from the electric arc to the metal bath was determined, with maximum temperature increase values of the metal amounting to 0.6 °C/min.*

Scientific novelty. *New data were obtained regarding the influence of neutral gas supply through GHE on the amount of heat transferred to the metal by convection, and indicators of the heat flux density from the electric arc to the metal cavity in the sub-electrode zone were determined.*

Practical significance. *It was determined that increasing the area of the metal cavity by supplying gas through the GHE channel improves the heat transfer from the electric arc to the metal bath. Meanwhile, increasing the thickness of the slag cover reduces heat losses to the furnace atmosphere. The carried out research provided important data regarding the thermal performance of the "ladle-furnace" in the sub-electrode zone, which can be further utilized for process optimization.*

Keywords: *ladle-furnace, graphitized hollow electrode, numerical modeling, 3D model, geometric parameters of the cavity, heat transfer, heat flux density.*

Introduction. The organization of technological processes in the "ladle-furnace" (LF) requires determining the sequence and timing of operations, which influences the consumption of energy and material resources. Therefore, the schemes for organizing these processes are continuously being improved. The efficiency of thermal processes during secondary steel refining in the "ladle-furnace" depends on various factors. In particular, the modification and removal of non-metallic inclusions, desulfurization, and steel alloying result in significant heat losses, which are compensated by heating through the electric arc formed between the lower end of the electrode and the metal bath.

One of the possible directions of development is the use of new materials and technologies that reduce energy consumption and increase equipment productivity. An option in this regard is the application of a graphitized hollow electrode (GHE) with gas supply through its channel, which increases the geometric parameters of the metal cavity, thereby positively impacting the efficiency of heat absorption from the electric arc.

Thus, the development of new technologies and equipment can improve the quality and efficiency indicators of secondary steel refining. Therefore, the research on the thermal performance of the graphitized hollow electrode with gas supply through its channel during steel processing in the "ladle-furnace" is a relevant task.

Relevance. During secondary metal processing, compensation for heat losses occurs through the heating of the metal by the heat released under the action of alternating or direct current electric arc. In the "ladle-furnace", the electric arc is formed between the metal and three vertically positioned graphitized electrodes (GE), creating a junction point of three arcs in the form of a "star" [1].

Approximate values characterizing the temperature drop of liquid steel in ladles with a capacity of 100-150 tons during desulfurization, deoxidation, alloying, holding-on, and ladle replacement are provided by the authors of works [2-4]. During desulfurization, when slag is formed and the melt is agitated by gas through bottom blowing devices or submerged lance, the steel temperature can decrease by 30-40 ºC. After the ferroalloys addition and subsequent homogenization of the chemical composition and temperature of the steel in the ladle, the temperature decreases by 10-15 °C. The rate of temperature decrease of the steel reaches up to 0.6 ºC/min during holding-on and ladle replacement, and 1.1-1.4 ºC/min during homogenization of the metal by inert gas blowing.

The practice at many metallurgical plants shows that during the secondary processing of a wide range of steel, the overall temperature decrease is 50-60 ºC or more. In the case of producing special steel grades using single or double vacuum technology, the temperature decrease can reach 150 to 250-300 ºC, respectively [2, 5, 6].

The rate of metal heating during processing in "ladle-furnace" ranges from 2 to 5 °C/min and depends on several technological parameters such as: heat accumulation and oxidation of electrodes; weight and rate of adding slag-forming materials; gas blowing regimes and flow rate; methods and locations of adding solid and powder materials; thickness of the slag layer; melt temperature; state of gas blowing blocks [3, 6, 7].

Based on the analytical review, there is a lack of reliable data on heat exchange in the "plasma-slag-metal" system, taking into account changes in the geometric parameters of the cavity and the formation of additional convective flows through gas injection through the channel of the graphitized hollow electrode.

This provides grounds to assert that research aimed at determining the influence of gas supply through the channel of the graphitized hollow electrode on heat transfer from the electric arc discharge to the metal bath during secondary processing is quite relevant.

Research methodology. Based on the results of previous studies on the influence of gas injection regimes through the channel of the hollow electrode, empirical regularities regarding the shape and size of the cavity have been defined. It is evident that changes in the geometric parameters of the cavity should affect the efficiency of heat transfer from the arc formed in the subelectrode zone to the metal melt on the "ladle-furnace". To evaluate this effect, computer modeling of non-stationary heat transfer in the "plasma-slag-metal" system was carried out.

In works [8-14], a significant number of various models used for numerical simulation of processes related to the transfer of energy, mass, momentum, and charge in the plasma of an electric arc are discussed.

To determine the effect of gas supply through the channel of the graphitized hollow electrode on the heat absorption efficiency of the metal, a comparison was made between different variants of secondary steel processing on the "ladle-furnace" with varying slag thickness and corresponding gas flow rate, proposed in the previous stage, and base variants without blowing with various slag thickness. The base variants were chosen to be the operation of a conventional graphitized electrode without gas injection with a slag thickness of 100-200 mm. The geometric parameters of the cavity under the given conditions were calculated in the previous stages of the research using models described in works [8, 15, 16]. In the next stage, initial conditions for calculating heat transfer in the plasma-slag-metal system were set, as presented in Table 1.

Using the software "Ansys", in the "DesignModeler", a 3D model of a ladle for steel casting with liquid metal and the cavity zone formed under the influence of an electric arc and gas was created. The geometric parameters of the 3D ladle model include a capacity of 250 tons with a metal level in the ladle of 3.96 meters and a bath diameter of 3.6 meters. To simplify the calculation, one-third of the total volume of the liquid bath was taken in the form of a part of truncated cone with a sector of a circle at its base, with the electrode axis located on the bisector of the angle of this sector. The distance of the GHE above the metal bath level is equal to 70 % of the thickness

Table 1

Initial conditions for heat transfer calculation

Parameter	Steel	Slag
Temperature *t*, ºC	1600	1700
Density ρ, kg/m^3	7000	3000
Thermal conductivity λ, W/(m·ºC)	60.5	0.45
Specific heat capacity, J/(kg·ºC)	434	1100

Table 2

Geometric parameters of the cavity

№	Gas flow rate through the GHE channel, m^3/h	Slag thickness, H_{sl}, m	Cavity depth, h_{cav}, m	Diameter of the circle at the base of the cavity, d_{cir}, m
1	No gas supply	0.1	0.05	0.495
2	No gas supply	0.2	0.04	0.495
3	3	0.1	0.07	0.499
4	4.5	0.1	0.08	0.502
5	6	0.1	0.09	0.507
6	6	0.2	0.06	0.608
7	8	0.2	0.07	0.626
8	10	0.2	0.08	0.644

of the slag cover [4]. The geometric parameters of the cavity for the base cases and the developed cases are provided in Table 2.

To obtain detailed information on any area of the investigated region, a computational grid was applied to the 3D model of the liquid bath, consisting of 12.098 elements and 41.368 nodes. Boundary conditions (bc) for the calculation of transient heat transfer were specified separately for each variant. For the electrode-slag interface, both in the base variants and with gas supply, Dirichlet (1st type) boundary condition was assigned, as the temperature in this region of the graphitized hollow electrode had been determined in the previous stage of the study [17]. For the slag and metal surfaces, Neumann (3rd type) boundary condition was specified, which was calculated based on the work [18].

Since the Grashof number for the given conditions is about 10^6, the convective heat transfer coefficient was determined using formula (1) for heat exchange during natural convection of liquid metals:

$$Nu \equiv \frac{\alpha \cdot h}{\lambda} = 0{,}52 Gr^{\frac{1}{4}} \cdot \mathrm{Pr}^{0{,}4}, \text{ where } Gr = 10^2 ... 10^9, \quad (1)$$

where α is the average heat transfer coefficient in $W/(m^2 \cdot {}^oC)$, h is the depth of the cavity formed between the metal and the slag, λ is the thermal conductivity of argon at high temperatures [19, 20].

The Grashof number (Gr) was calculated using the formula:

$$Gr = \frac{g \beta d_{GHE}^3 \left(T_{amb} - T_{aver}\right)}{v_g} \cdot 10^{-3}, \quad (2)$$

where g = 9,81 m/s^2 is acceleration of gravity; $\beta = 1/T_{surf}$ — volume expansion coefficient of gases, K^{-1}; d_{GHE} — diameter of the graphitized hollow electrode, m; ($T_{amb} - T_{aver}$) — the temperature difference between the atmosphere in the arc burning zone and the average temperature of the metal surface and the atmosphere, K; v_g — coefficient of kinematic gas viscosity, m^2/s.

Pr — the Prandtl number was calculated using the formula:

$$\mathrm{Pr} = v_g / a, \quad (3)$$

where a — thermal diffusivity, m^2/s.

Thus, the following boundary conditions were adopted for the calculation of unsteady heat transfer during processing of steel in a "ladle-furnace", as presented in Table 3.

The calculation of the increase in specific heat Δi of liquid steel through the metal mirror surface (without

Table 3

Boundary conditions for unsteady heat transfer

Surface	Type of boundary conditions	Convective heat transfer coefficient α, $W/(m^2 \cdot {}^oC)$	Ambient temperature T_{amb}, °C	Emissivity ε [21]
Contact of slag with the lateral surface of the electrode	Dirichlet (1st type bc)	—	2500	—
Surface of the slag in the arc burning zone	Neumann (3rd type)	8.07	4500	0.9
Surface of the metal in the arc burning zone	Neumann (3rd type)	8.15	4500	0.4

considering heat losses through the walls and bottom of the ladle) during heating in the "ladle-furnace" was performed using the following formula:

$$\Delta i = \frac{F}{m}\int q(\tau)\,d\tau,\ \text{J/kg}, \qquad (4)$$

where F is the surface area of the metal mirror, m²; m is the mass of steel, kg; $q(\tau)$ is the time-varying change in the average value of the heat flux density over the area F, W/m²; τ is the time, s. The surface area of the metal mirror was determined based on the given parameters in the "DesignModeler".

Since the calculation results of the average heat flux density function were obtained in a discrete form, it was necessary to apply a numerical integration method for the calculation of the specific heat increment. Among the known methods, the Simpson's method was chosen for its sufficient accuracy and reliable results. This method was implemented using the Microsoft Excel.

This method of computing a definite integral is based on replacing the graph of the integrand function with parabolic arcs whose axes are parallel to the Oy axis, rather than using straight chords as in the trapezoidal method. If the integration interval [a; b] is divided into an even number of equal parts (i.e., $n = 2m$) and denoted by $y = f(x_k)$, where $x_k = a + \Delta x \cdot k$ represents the division points with $k = 0, 1, 2, \ldots, 2m$, then the definite integral can be computed using the formula [21-24]:

$$\int_a^b f(x)\,dx \approx \frac{b-a}{6m}\Big(y_0 + y_{2m} + 2\big(y_2 + y_4 + \ldots + y_{2m-2}\big) + 4\big(y_1 + y_3 + \ldots + y_{2m-1}\big)\Big). \qquad (5)$$

Here, the number of division points $2m$ is arbitrary, but the larger this number, the more accurate the sum on the right-hand side of the equation provides the value of the integral.

Modeling results. The modeling results provide data on the distribution of heat flux density through the curved surface of the metal cavity and the surface of the slag in the sub-electrode zone during the steel processing in the "ladle-furnace". This distribution is depicted in Fig. 1 as a set of vectors with different directions on the 3D model of the sub-electrode zone during metal treatment in the "ladle-furnace", under the conditions of a slag height of 100 mm and a gas flow rate supplied through the GHE channel of 3 m³/h.

The magnitude and main directions of the heat flux density distribution vectors have been determined, of which the majority is directed through the curved cavity formed by the action of the electric arc into the volumes of the metal bath and slag layer.

Based on the obtained distribution data, separate graphs of the average heat flux density distribution have been constructed for the surface of the metal cavity and the surface of the slag, considering a gas flow rate of 3 m³/h supplied through the channel of the graphitized hollow electrode and a slag layer height of 100 mm (Fig. 2).

From the data shown in Fig. 2, it can be observed that at the beginning of the process, the heat flux density sharply increases, reaching its peak and then starts to decrease. This phenomenon can be explained by the fact that at the start of the operation of the electric arc device, the temperature of the surfaces of the liquid steel and slag in the arc burning zone rapidly increases, leading to a significant increase in heat flux density. Subsequently, the heat flux density gradually decreases after reaching its peak due to the redistribution of temperature from the surfaces of the steel and slag into their overall volumes. This dependence is relevant for both steel and slag, despite the fact that the heat flux density to the slag is higher than to the steel due to its higher emissivity.

For the calculation of the increase in specific heat content of the liquid steel through the metal mirror surface, the share of heat transferred to the metal through radiation and convective heat transfer were determined. The influence of the gas flow rate supplied through the channel of the graphitized hollow electrode on the portion of heat transferred to the metal through convective

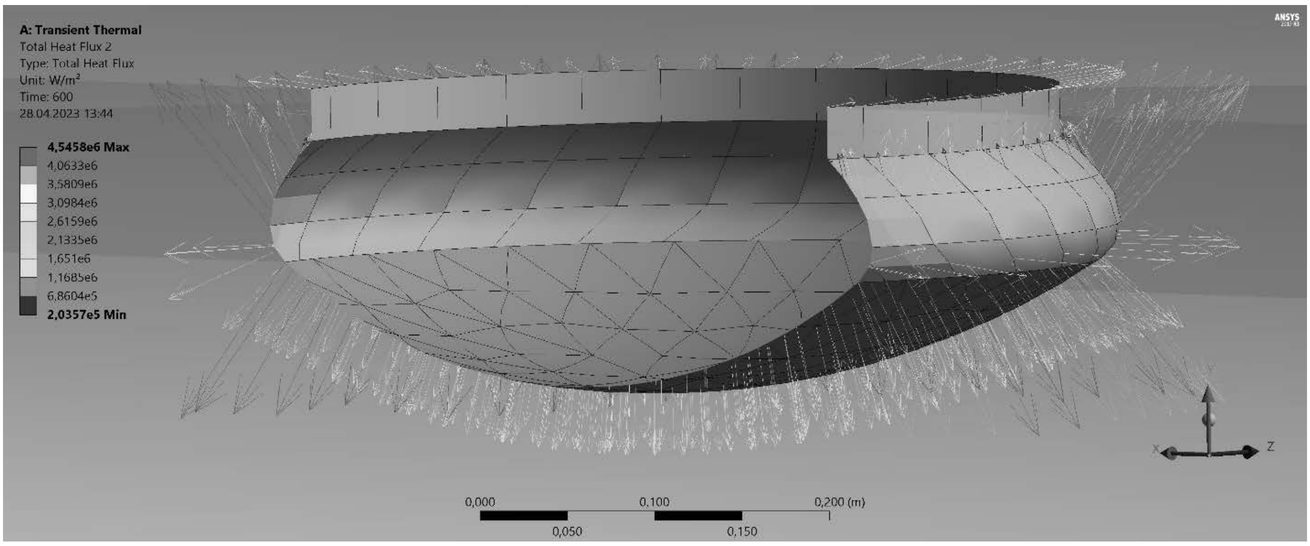

Fig. 1. Distribution of heat flux density through the surface of steel and slag in the sub-electrode zone

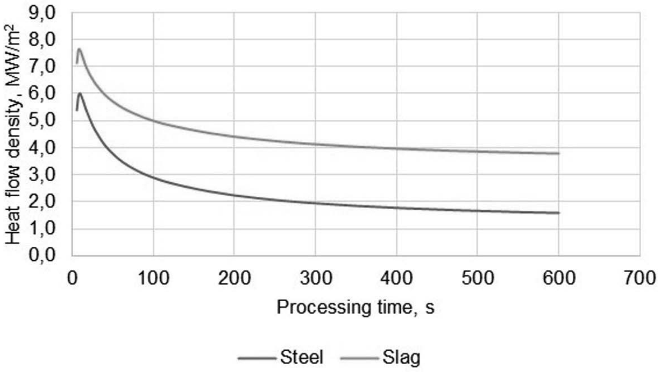

Fig. 2. Change in the average heat flux density through the surface of steel and slag in the sub-electrode zone

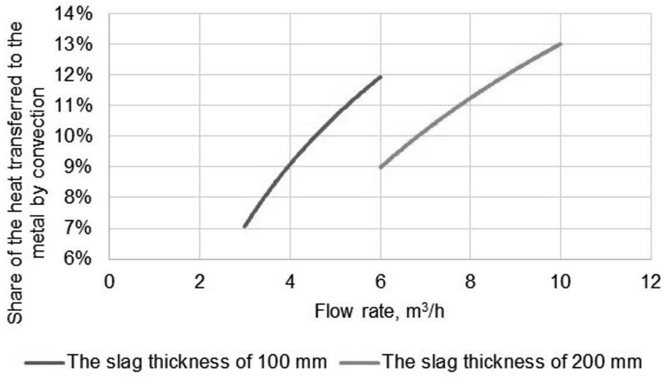

Fig. 3. The effect of gas consumption on the share of heat transferred by convection

heat transfer in the arc zone during the operation of the "ladle-furnace" is depicted in Fig. 3.

The investigated range for a slag layer height of 100 mm varied from 3 to 6 m^3/h, while for a slag layer thickness of 200 mm, it ranged from 6 to 10 m^3/h. It has been determined that the share of heat transferred to the metal bath by convection during the operation of the electric arc device in the "ladle-furnace" increases with an increase in the gas flow rate supplied through the GHE channel. This dependence is characteristic for slag layer thickness of 100-200 mm. The difference lies in the fact that with a larger induced slag layer, at the same gas flow rate, the share of heat transferred by convection will be smaller. This phenomenon can be explained by the fact that as the slag volume increases, the distance of the electrode tip above the level of the metal bath also increases to a degree that its value is equal to 70 % of the slag layer thickness, which leads to a deterioration in convective heat transfer.

Additionally, based on the obtained data, the fractions of heat absorbed by the metal bath and slag layer were calculated and plotted for the use of a conventional GE without gas supply and a hollow GE with gas supply through its channel at rates of 4.5 m^3/h and 8 m^3/h, respectively, with a slag layer thickness of 100 mm and 200 mm, respectively.

A circular diagram comparing the aforementioned modes with a slag layer thickness of 100 mm has been constructed, as shown in Fig. 4. When using a regular electrode without gas supply, the share of heat obtained by the metal reaches 81 %, while the slag accounts for 19 %. However, when using a GHE with gas supplied through its channel, the share of heat obtained by the metal increases by 2 % and reaches 83 %, while the slag share decreases to 17 %. The increase in the share of heat absorbed by the metal when gas is supplied through the GHE channel is due to the enlargement of the effective surface area for heat exchange.

The comparison of the share of heat absorbed by the slag and metal during gas injection through the GHE channel and during the use of a regular electrode without gas supply in the sub-electrode zone is presented in Fig. 5, considering a slag layer thickness of 200 mm.

Similar to the previous diagram, it can be observed that the share of heat absorbed by the metal is lower when using a regular electrode without gas injection compared to when gas is supplied through the GHE channel. Specifically, without gas supply, the share of heat transferred to the metal is 67 %, while to the slag layer it is 33 %. However, when gas is injected into the sub-electrode zone, the share of heat absorbed by the metal increased by 7 %, reaching 74 %, while the share absorbed by the slag decreased to 26 %. The increased slag mass ensures more efficient heat absorption by the metal bath, reducing heat losses to the furnace atmosphere.

Fig. 6 illustrates the influence of gas flow rate and slag layer thickness on the temperature increase of the steel

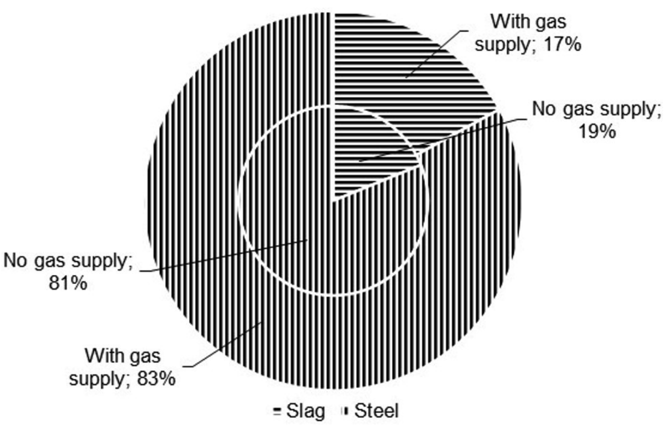

Fig. 4. Comparison of the absorbed share of heat by the metal and slag during gas injection through the GHE channel with and without it, with a slag layer thickness of 100 mm

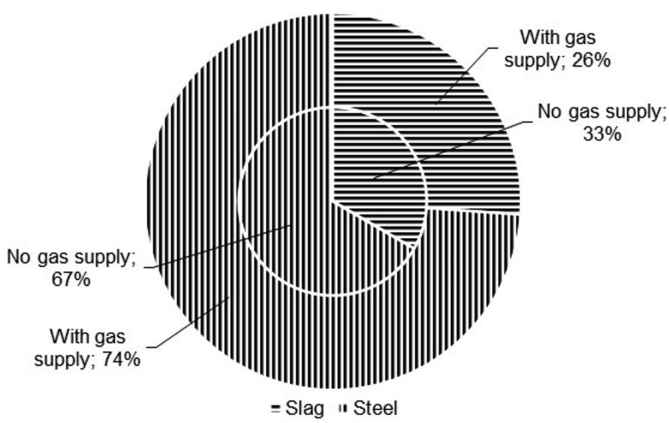

Fig. 5. Comparison of the absorbed share of heat by the metal and slag during gas injection through the GHE channel with and without it, with a slag layer thickness of 200 mm

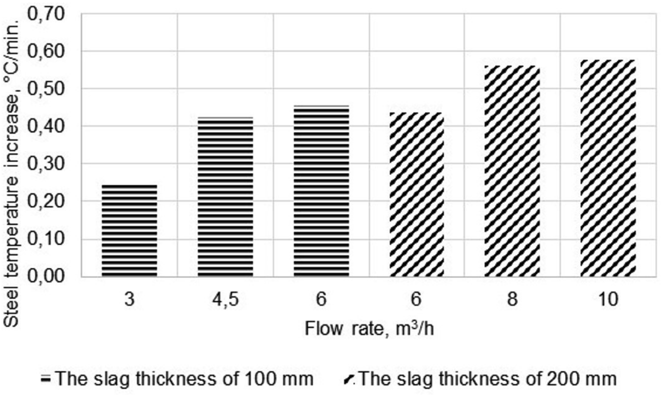

Fig. 6. Influence of gas flow rate and slag layer thickness on the temperature increase of steel

during gas injection through the GHE in steel treatment in the “ladle-furnace”. Based on the aforementioned data of the investigated region, the heating rate of the liquid steel was calculated to compare the proposed injection modes with the baseline variant without injection. In the baseline variant, the heating rate was 2.8 ºC/min.

Gas injection through the GHE channel leads to an increase in the heating rate of the metal, depending on the gas flow intensity and slag layer thickness. This value ranges from 0.2 to 0.5 ºC/min for a slag layer height of 100 mm, and from 0.4 to 0.6 ºC/min for 200 mm of slag. This can be explained by the fact that the geometric parameters of the cavity formed under the action of the electric arc depend on the distance of the electrode tip and the gas flow rate supplied through the GHE channel. With an increase in gas flow rate, the diameter and depth of the cavity increase, thereby improving the performance of the electric arc discharge by increasing the contact area between them.

Conclusions

The results of the carried out modeling provide data on the distribution of heat flux density through the curved surface of the metal and slag cavity in the sub-electrode zone during steel treatment in the “ladle-furnace”. The maximum values of heat flux density to the metal reach 6 MW/m^2, while to the slag, it reaches 7.7 MW/m^2.

The obtained data provide information about the heat transfer by convection in the sub-electrode zone under different processing conditions in the “ladle-furnace”. With gas flow rate of 3-6 m^3/h and a slag layer height of 100 mm, the proportion of heat transferred to the metal by convection ranges from 7 % to 12 %, while with gas flow rate of 6-10 m^3/h and a slag layer thickness of 200 mm, it ranges from 9 % to 13 %.

The share of heat absorbed by the slag and metal has been determined under the conditions of using a conventional electrode and a GHE with gas flow through its channel. With a slag layer thickness of 100 mm and gas injection through the GHE channel, the share of heat absorbed by the metal increases by 2 % compared to the use of a conventional electrode. With a slag layer thickness of 200 mm, this share increases by 7 %.

The heating rate of liquid steel has been calculated when using a conventional electrode (without gas injection), which amounts to 2.8 ºC/min. The temperature increase, at the recommended gas flow rate of 3-6 m^3/h and a slag layer thickness of 100 mm, ranges from 0.21 to 0.43 ºC/min. With gas flow rate of 6-10 m^3/h and a slag layer thickness of 200 mm, the temperature increase ranges from 0.47 to 0.61 ºC/min.

The supply of neutral gas in the range of 3 to 10 m^3/h, with a slag layer thickness of 100-200 mm, improves the thermal performance of the “ladle-furnace”.

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Дослідження теплової роботи графітованого порожнистого електрода установки «ківш-піч» при подачі нейтрального газу

У статті виконано аналіз ефективності передачі теплоти від електродугового розряду, сформованого в піделектродній зоні, до металевої ванни за різних умов роботи установки «ківш-піч» (УКП). Розроблено методику чисельного моделювання, проаналізовано отримані дані, визначено ефективність передачі теплоти з подачею нейтрального газу через графітований порожнистий електрод (ГПЕ).
Метою цієї роботи *є чисельне моделювання впливу зміни геометричних параметрів лунки металу, яка сформована за рахунок вдування газу каналом графітованого порожнистого електрода на ефективність передачі теплоти від електричної дуги до металевої ванни при різній висоті шлакового покрову на установці «ківш-піч».*
Методи дослідження. *Чисельне моделювання нагріву металевої ванни на розробленій 3D моделі сталерозливного ковша з рідким металом і зоною лунки, утвореної під дією електричної дуги, та газу, який подається каналом графітованого порожнистого електрода. Нагрівання проводилося за різних геометричних параметрів лунки та різної висоти шлакового покрову. Виконано аналіз отриманих даних, який вказав на перевагу використання графітованого порожнистого електрода з подачею газу його каналом перед звичайним електродом.*
Отримані результати. *Визначено частку теплоти, яку поглинули шлак і метал за умов використання звичайного електрода, та порожнистого з подачею газу його каналом. Визначено вплив параметрів реакційної зони, що формується під ГПЕ на передачу теплоти від електричної дуги до металевої ванни, максимальні значення приросту температури металу склали 0,6 °С/хв.*
Наукова новизна. *Отримані нові дані щодо впливу подачі нейтрального газу через ГПЕ на кількість теплоти, що пе-*

редається металу конвекцією, визначені показники густини теплового потоку від електричної дуги до лунки металу в піделектродній зоні.

Практична цінність. *Визначено, що за рахунок збільшення площі металевої лунки за допомогою подачі газу каналом ГПЕ покращується теплопередача від електричної дуги до металевої ванни. В той час як збільшення товщини шлакового покрову зменшує теплові втрати в атмосферу печі. Проведені дослідження дозволили отримати важливі дані стосовно теплової роботи установки «ківш-піч» в піделектродній зоні, які в подальшому можуть бути використані для вдосконалення виробничих процесів.*

Ключові слова

Установка «ківш-піч», графітований порожнистий електрод, чисельне моделювання, 3D модель, геометричні параметри лунки, теплопередача, густина теплового потоку.