



UDC 669.162.221.2

DOI 10.17073/0368-0797-2024-2-148-154



Original article

Оригинальная статья

ESTIMATION OF ACCIDENT RATE OF BLAST FURNACE TUYERES

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Abstract. In modern blast furnace production, even a short-term disruption of the technological process is associated with large productivity losses. In the practice of conducting blast furnace melting, there are often significant deviations from the optimal mode. They can lead not only to disruptions of the blast furnace, but also to accidents. In the operation of a blast furnace, typical deviations from the normal distribution of gas flow and charge materials include: peripheral, axial, channel passages; skewing of the backfill level; varying degrees and types of charge suspension. As a result, there are a cooling or excessive overheating of the furnace and violation of the melting operation. A serious consequence of the prolonged peripheral movement of gases is not only intensive wear of the lining, poor use of thermal and chemical energy of gases, but also stable cluttering of the hearth with formation of a deadman. Deadman is an ore-coke sinter formed in the tuyere zone of a blast furnace, as a result of cooling of its center. The paper describes the study and analysis of violations of blast furnace operation, analysis of the deadman causes and assessment of the accident rate of blast furnace tuyeres. Violation of gas distribution and hearth cluttering lead to formation of a deadman, which provokes mass burning of tuyeres and blast furnace refrigerators. The developed methodological foundations (mathematical model) allow us to estimate the maximum temperature of the tuyere zone and the resulting heat flow to the tuyere toe in presence of a deadman. It is shown that in large-volume blast furnaces, bubble outflow of the gas-coal flow prevails, contributing to growth of a deadman in the blast furnace.

Keywords: ferrous metallurgy, blast furnace production, blast furnace, tuyere, deadman, tuyere zone, temperature increase, resulting heat flow, burnout

For citation: Stuk T.S., Pototskii E.P. Estimation of accident rate of blast furnace tuyeres. *Izvestiya. Ferrous Metallurgy*. 2024;67(2):148–154.
<https://doi.org/10.17073/0368-0797-2024-2-148-154>

ОЦЕНКА АВАРИЙНОСТИ ДОМЕННЫХ ФУРМ

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Аннотация. В современном доменном производстве даже кратковременное нарушение технологического процесса связано с большими потерями производительности. В практике ведения доменной плавки нередко встречаются значительные отклонения от оптимального режима. Они могут приводить не только к расстройкам хода доменной печи, но и к авариям. В работе доменной печи к типичным отклонениям от нормального распределения потока газа и шихтовых материалов относят: периферийный, осевой, каналный ходы; перекося уровня засыпи; различной степени и вида подвеса шихты. Вследствие этого происходят похолодание или излишний перегрев печи, нарушение ровности хода. Тяжелым последствием длительного периферийного движения газов являются не только интенсивный износ кладки, слабое использование тепловой и химической энергии газов, но и стабильное загромождение горна с образованием тотермана. Тотерман – это рудно-коксый спек, образующийся в фурменной зоне доменной печи в результате похолодания ее центра. Данная работа посвящена исследованию и анализу нарушений работы доменной печи, анализу причин возникновения тотермана, оценке аварийности фурм доменной печи. Нарушение газораспределения и загромождение горна приводят к образованию тотермана, который провоцирует массовое горение фурм и холодильников доменной печи. Разработанные методические основы (математическая модель) позволяют оценить максимальную температуру фурменной зоны и результирующий тепловой поток на носок фурмы при наличии тотермана. Показано, что в доменных печах большого объема преобладает пузырьковый поток истечения газо-угольного потока, способствующий росту тотермана доменной печи.

Ключевые слова: черная металлургия, доменное производство, доменная печь, фурма, тотерман, фурменная зона, повышение температуры, результирующий тепловой поток, прогар

Для цитирования: Стук Т.С., Потоцкий Е.П. Оценка аварийности доменных фурм. *Известия вузов. Черная металлургия*. 2024;67(2): 148–154. <https://doi.org/10.17073/0368-0797-2024-2-148-154>

INTRODUCTION

As of today, the industrial safety policy of metallurgical companies is based on the assertion that accidents and emergencies at production facilities can be prevented. Therefore, to prevent accidents at enterprises, various methods for hazard analysis and risk assessment are actively implemented and used.

Despite the trend towards reducing the number of accidents, the frequency of incidents in metallurgical production remains consistently high. The number of accidents ranges from 4 to 9 annually, but their distribution across different metallurgical production processes varies¹ (Fig. 1). The most hazardous processes include blast furnace, oxygen converter, electric furnace steelmaking, and coke-chemical productions.

The most severe types of accidents in blast furnace production involve the removal of pig iron and/or slag from metallurgical units, breakthrough of the hearth, refrigerators, and air ducts of blast furnaces, as well as explosions in metallurgical units caused by the supply of charge materials and tuyere burnouts [1; 2].

According to the 2020 report by PJSC NLMK, blast furnace tuyeres failed more than 200 times (Fig. 2). Fig. 3 presents the statistics of blast furnace tuyere failures as a percentage.

Typical deviations from the normal distribution of gas flow and charge materials include peripheral, axial, and channel passages; skewing of the backfill level; and various degrees and types of charge suspension, including the so-called “tight” run [3; 4]. Consequently, the furnace may experience cooling or excessive overheating, overloading of the axial zone with mineral charge,

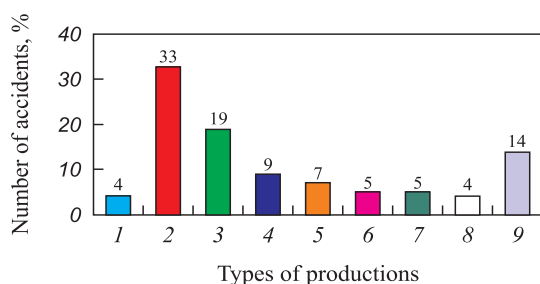


Fig. 1. Distribution of accidents by type of production:

1 – agglomeration; 2 – blast furnace; 3 – oxygen converter; 4 – coke-chemical; 5 – foundry; 6 – oxygen production; 7 – rolling; 8 – ferroalloy; 9 – electric furnace steelmaking

Рис. 1. Распределение аварий по видам производств:

1 – агломерационное; 2 – доменное; 3 – кислородно-конвертерное; 4 – коксохимическое; 5 – литейное; 6 – производство кислорода; 7 – прокатное; 8 – ферросплавное; 9 – электросталеплавильное

¹ Annual Report on the Activities of the Federal Service for Environmental, Technological, and Nuclear Supervision for the period from 2010 to 2020. URL: https://www.gosnadzor.ru/public/annual_reports/ (accessed on: January 25, 2024).

and violation of the melting operation. These conditions can lead to the cluttering of the hearth and frequent burning of the air tuyeres. Prolonged channel passages result in uneven burnout of the profile or stagnation of charge materials, leading to the formation of accretions [5].

Hearth cluttering in blast furnaces adversely affects the thermal mode, necessitating a reduction in ore loads. In the hearth, significant amounts of graphite form at lower temperatures [6]. The heating of the hearth deteriorates due to the formation of peripheral passages, as there is a decrease in heating when unprepared charge material is loaded [4]. Cold ferri-ferrous slag forms on the tuyeres.

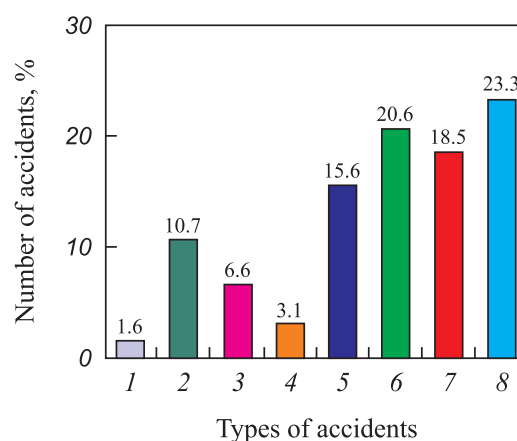


Fig. 2. Main types of accidents:

1 – rupture of blast furnace jacket; 2 – rupture of large diameter pipelines; 3 – explosion in metallurgical units; 4 – building collapse; 5 – fire; 6 – removal of cast iron and/or slag from metallurgical units; 7 – breakthrough of the hearth, refrigerators, air ducts of blast furnace; 8 – explosion in metallurgical units due to supply of raw charge and tuyeres burnout

Рис. 2. Основные виды аварий:

1 – разрыв кожуха доменной печи; 2 – разрыв трубопроводов большого диаметра; 3 – взрыв в металлургических агрегатах; 4 – обрушение здания; 5 – пожар; 6 – уход чугуна и/или шлака из металлургических агрегатов; 7 – прорывы горна, холодильников, воздухопроводов доменной печи; 8 – взрывы в металлургических агрегатах из-за подачи сырой шихты и прогара фурм

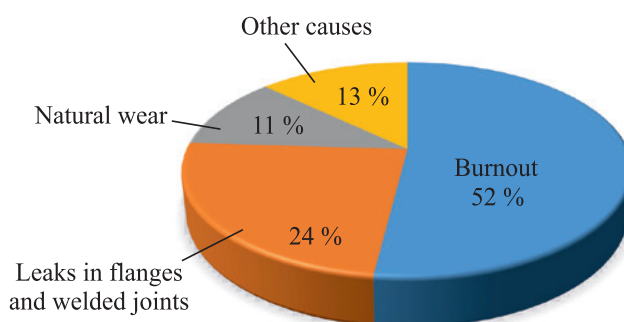


Fig. 3. Failure statistics of blast furnace tuyeres

Рис. 3. Статистика отказов доменных фурм

The infiltration of water vapor into the hearth through burnouts of cooling equipment is further exacerbated by the overloading of the low-mobility zone in the presence of low kinetic energy [7]. This deviation leads to the cluttering process in the tuyere belt of the blast furnace. As the cluttering zone expands, the burning of tuyere connections intensifies, as depicted in Fig. 4.

A severe disruption of the smelting process is the clogging of the hearth [4; 8]. It contributes to the deterioration of the gas dynamics of the process and significantly reduces the working space of the iron receiver. This hinders the movement of molten iron in the hearth and clogs the space in front of the tuyere nose. When the center of the blast furnace hearth cools, coke and slag begin to compress into a monolith due to the fine fraction of the charge material [9; 10]. This leads to poor filtration in the hearth, thus making it difficult for the smelting products to flow into the blast furnace iron receiver.

Despite the numerous developed and applied methods for assessing the risk of accidents in blast furnace production, a methodology is needed that can account for the specific operational characteristics of the blast furnace, considering the formation of the deadman in the tuyere zone and the increase in temperature in the tuyere zone with subsequent tuyere burnout, etc. Therefore, improving the methodology for assessing the accident risk of blast furnace tuyeres, taking into account the formation of the deadman, is currently a relevant task.

DESCRIPTION OF THE RESEARCH METHOD

A significant contribution to the study of tuyere zone cluttering has been made by the National University of Science and Technology MISiS (NUST MISiS)

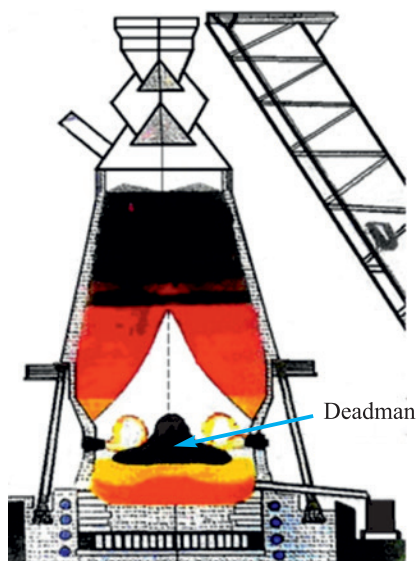


Fig. 4. Hearth cluttering with ore-coke sinter

Рис. 4. Процесс загромождения горна рудно-коксовым спеком

through the efforts of Zherebin B.N., Vegman E.F., Parenkov A.E., and others [1; 11]. It is known that large-volume blast furnaces (Blast Furnace No. 5 of the Kryvorizhstal plant) are prone to the formation of large scabs, including ore-coke sinter, in the central part of the hearth. The boulder-like formation (deadman), with its peak reaching the level of the bosh, consists of refractory carbides and carbonitrides. The deadman obstructs normal gas distribution and promotes the formation of a peripheral flow in the blast furnace [12; 13]. The tuyere blast reflects off the surface of the deadman onto the furnace lining and hearth refractory. This leads to a deterioration in the durability of the refractory and contributes to an emergency situation due to the breakthrough of high-temperature smelting products in the blast furnace.

This work proposes a methodology for assessing the accident rate of blast furnace tuyeres under the influence of a deadman.

In blast furnaces, two stable hydrodynamic outflow modes are realized: jet and bubble [14; 15]. The jet mode of flow is characteristic of normal gas distribution in the blast furnace, whereas the bubble mode of flow promotes the growth of the deadman.

The value of the Glinkov criterion G_n is determined by the formula

$$G_n = \frac{\rho_g w_g^2}{\rho_j g h_j}, \quad (1)$$

where ρ_g is the effective density of the flow, kg/m³; w_g is the gas velocity at the tuyere exit, m/s; ρ_j is the density of the melt in the tuyere zone, kg/m³; g is the acceleration due to gravity, m/s²; and h_j is the distance from the tuyere axis to the melt, m.

The effective density of the flow is calculated using the formula

$$\rho_g = Q_{\text{air}} \rho_{\text{hb}} + Q_{\text{ng}} \rho_{\text{ng}} + Q_{\text{coal}} \rho_{\text{coal}}, \quad (2)$$

where Q_{air} , Q_{ng} , Q_{coal} are the volumetric fractions of “air + oxygen,” natural gas, and pulverized coal; ρ_{hb} , ρ_{ng} , ρ_{coal} are the densities of hot blast, injected natural gas, and pulverized coal.

The density of the hot blast is calculated using the formula

$$\rho_{\text{hb}} = \rho_0 \frac{PT_0}{P_0 T_b}, \quad (3)$$

where ρ_{hb} is the density of the hot blast, kg/m³; ρ_0 is the density of air under normal conditions, kg/m³; P is the pressure of the hot blast, atm; P_0 is the atmospheric pressure, atm; T_0 is the ambient temperature, K; T_b is the blast temperature, K.

Density of the injected natural gas is determined using the formula

$$\rho_{ng} = \rho_0^{ng} \frac{P}{P_0}, \quad (4)$$

where ρ_0^{ng} is the density of natural gas, kg/m³.

If the Glinkov criterion is less than one, a bubble mode is present; if the Glinkov criterion exceeds three, the flow mode is jet. Intermediate values indicate a transitional flow mode.

The heat transfer from the deadman primarily occurs through radiation and convection. To calculate the resultant heat flow to the tuyere nose, it is necessary to determine the temperature of the internal blowing zone and the hydrodynamic blowing mode of the blast furnace. The temperature of the blowing zone corresponds to the surface temperature of the deadman [1].

The surface temperature of the deadman T_t can be calculated from the heat balance equation using the formula [16]

$$T_t = \frac{0.165T_f V_{bost}}{d_h^3} + 2.445(B - 483) + 2.91(T_j - 107) - 11.2(\eta_{CO} - 27.2) + 28.9(d_{proke} - 25.8) + 326, \quad (5)$$

where T_f is the theoretical combustion temperature, °C; V_{bost} is the volume of gas in the bosh, mm³/min; d_h is the diameter of the hearth, m; B is the fuel consumption, kg/t; T_j is the index of slag fluidity; η_{CO} is the CO content in the furnace center (from the shaft); d_{proke} is the diameter of coke particles in the deadman, mm.

The index of slag fluidity (T_j) is calculated using the formula

$$T_j = T_{mi} - \left\{ 342 \left(\frac{CaO}{SiO_2} \right) + 11.0[(Al_2O_3) + 1.4] + 819 \right\}, \quad (6)$$

where T_{mi} is the temperature of the molten iron, °C; $\left(\frac{CaO}{SiO_2} \right)$ is the basicity of the slag; and (Al_2O_3) concentration of Al_2O_3 in the slag, %.

The size of the blowing zone, i.e., the zone where the horizontal gas-liquid flow and the reaction zone are located, is determined using the formula

$$l_{bz} = 5.44d_0 \left(G_n \frac{H_0}{d_0} \right)^{0.24}, \quad (7)$$

where l_{bz} is the length of the blowing zone, m; H_0 is the height of the liquid bath, m; d_0 is the inner diameter of the tuyere nose, m.

The effective emissivity of the tuyere nose is calculated using the formula

$$\varepsilon_{ef} = \frac{1}{1 + \left(\frac{1}{\varepsilon_l} - 1 \right) \frac{S}{S_l}}, \quad (8)$$

where ε_{ef} is the effective emissivity of the tuyere nose; ε_l is the emissivity of the tuyere nose (assumed to be 0.6); S_l is the area of the inner surface of the blowing zone, m; S is the area of the metal casing of the tuyere nose, m².

The area of the metal casing of the tuyere nose S is determined using the formula

$$S = 0.785(d_n^2 - d_0^2), \quad (9)$$

where d_n is the outer diameter of the tuyere nose, m; d_0 is the inner diameter of the tuyere nose, m.

The area of the inner surface of the blowing zone S_l is calculated using the formula

$$S_l = \pi d_n l_{bz}, \quad (10)$$

where l_{bz} is the length of the blowing zone, m.

The resultant heat flow q^p to the tuyere nose [13] is calculated using the Stefan-Boltzmann law:

$$q^p = \varepsilon_{ef} \sigma (T_t^4 - T_l^4), \quad (11)$$

where ε_{ef} is the effective emissivity of the tuyere nose; σ is the Stefan-Boltzmann constant, equal to $5.67 \cdot 10^{-8}$ W/(m²·K⁴); T_t is the surface temperature of the deadman, K; T_l is the temperature of the multi-phase flow at the tuyere section, K.

CONDUCTED RESEARCH AND ANALYSIS OF ITS RESULTS

It is assumed that from the furnace throat to the bosh, there is a dense layer through which the ascending gases filter. The bubbling layer is located in the zone between the bosh and the hearth [15; 17]. The charge in the bubbling layer is in a liquid state. The blast streams, in addition to air, oxygen, and natural gas, carry pulverized coal particles [18]. According to Table 1, the Glinkov criterion was determined.

Using formulas (3) and (4), the values $\rho_{hb} = 0.61$ kg/m³, $\rho_{ng} = 2.08$ kg/m³ were determined. The effective density of the flow, calculated using formula (2), is 0.79 kg/m³, and the Glinkov criterion, using formula (1), is 0.27, indicating a bubble mode for the gas-coal flow in the blast furnace.

Next, the average surface temperature of the deadman was determined. The initial data for the calculation are presented in Table 2.

Using formula (6), the index of slag fluidity T_f was calculated to be 837 °C, and the surface temperature

Table 1. Initial data for calculating the Glinkov criterion

Таблица 1. Исходные данные для расчета критерия Глинка

Title	Designation	Numerical value
Distance from the tuyere axis to the melt, m	h_j	5.8
Gas velocity at the tuyere exit, m/s	w_g	250
Blast temperature at the tuyere exit, °C	T_b	1255
Density of pulverized coal, kg/m ³	ρ_{coal}	1400
Density of air, kg/m ³	ρ_0	1.3
Hot blast pressure, atm	P	2.6
Ambient temperature, K	T_0	273
Density of natural gas, kg/m ³	ρ_0^{ng}	0.8
Air pressure, atm	P_0	1
Melt density in the tuyere zone, kg/m ³	ρ_j	3200
Acceleration due to gravity, m/s ²	g	9.8

of the deadman T_t using formula (5), was 2331 °C, which exceeds the theoretical combustion temperature by 231 °C.

To calculate the resultant heat flow on the tuyere nose of the blast furnace, we assume the following:

- the blowing zone is a cylindrical cavity with a diameter equal to the outer diameter of the tuyere;
- the surface temperature of the deadman T_t is 2331 °C;
- the output parameters of the tuyere, including the multiphase flow at this section, have a temperature T_1 of 800 °C;
- the gas flow in the blowing zone is filled with coal particles and melt droplets [18]. Radiation in this zone follows the laws of blackbody radiation.

The initial data for calculating the heat flux to the tuyere nose are presented in Table 3.

Table 3. Initial data for calculating the heat flow on tuyere toe

Таблица 3. Исходные данные для расчета теплового потока на носок фурмы

Title	Designation	Numerical value
Inner diameter of the tuyere nose, m	d_0	0.15
Outer diameter of the tuyere nose, m	d_n	0.25
Height of the liquid bath, m	H_0	5,8
Emissivity of the tuyere nose cut	ε_l	0,6
Surface temperature of the deadman, K	T_t	2573
Temperature of the multiphase flow at the tuyere section, K	T_1	1073

Table 2. Initial data for calculating the average deadman temperature

Таблица 2. Исходные данные для расчета средней температуры тотормана

Title	Designation	Numerical value
Theoretical combustion temperature, °C	T_f	2100
Volume of gas in the bosh, mm ³ /min	V_{bosh}	3.7
Diameter of the hearth, m	d_h	10.85
Fuel consumption, kg/t	B	500
CO content in the furnace center, %	η_{CO}	25 – 34
Diameter of coke particles in the deadman, mm	d_{proke}	up to 20
Temperature of molten iron, °C	T_{mi}	1250
Basicity of slag	(CaO/SiO ₂)	2 – 3
Concentration of Al ₂ O ₃ in slag, %	(Al ₂ O ₃)	6 – 10

The length of the blowing zone, determined using formula (7), is 1.43 m. The effective emissivity of the tuyere nose, calculated using formula (8), is 0.953. The area of the metal casing of the tuyere nose S , determined using formula (9), is 0.033 m², and the area of the inner surface of the blowing zone S_l using formula (10), is 1.123 m². The resultant heat flow q^p to the tuyere nose, determined using formula (12), is 2.3 MW/m².

In stationary mode (heating the tuyere), there is local contact between the tuyere nose and the pig iron. The allowable resultant flux on the tuyere nose should not exceed 2.1 MW/m² [19], indicating that further reducing the cooling water temperature for the tuyere is impractical and leads to thermal stresses. This reduction decreases the lifespan of the tuyere device and can provoke mass tuyere burnouts.

The increase in tuyere zone temperature for different volumes of blast furnaces indicates the need for additional measures to prevent tuyere burnouts. Fig. 5 shows this dependence.

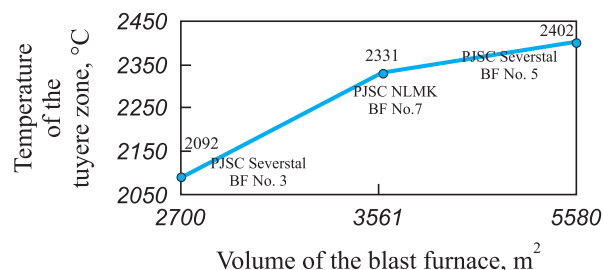


Fig. 5. Dependence of tuyere zone temperature on blast furnace volume

Рис. 5. Зависимость температуры фурменной зоны от объема доменной печи

Thus, the surface temperature of the deadman depends on the volume of the blast furnace. The temperature rise negatively impacts the safe operation of large-volume blast furnaces, increasing the likelihood of gas explosions and reducing the lifespan of tuyere devices.

Accidents involving mass tuyere burnouts are associated with intense vaporization. They are accompanied by a large amount of water entering the blast furnace [20]. The resulting steam breaches from beneath the layers of pig iron and slag cause chain-like thermal explosions.

RECOMMENDATIONS FOR PREVENTING TUYERE BURNOUT

The study proposes measures to prevent tuyere burnout depending on the volume of the blast furnace and the temperature of the tuyere zone.

For blast furnaces with a volume up to 2700 m³ and a tuyere zone temperature up to 2100 °C:

- automated analysis of retrospective data on the statistical properties of cooling water flow rate variations;
- analysis of silicon content in pig iron.

For blast furnaces with a volume of 2700 – 3500 m³ and a tuyere zone temperature of 2100 – 2300 °C:

- automated analysis of retrospective data on the statistical properties of cooling water flow rate variations;
- analysis of silicon content in pig iron;
- the nose of the air tuyere must be protected with refractory materials, including plasma spraying;
- the inner sleeve of the tuyere must be made of steel plate instead of copper, with additional lining of refractory materials.

For blast furnaces with a volume of 3500 – 5560 m³ and a tuyere zone temperature of 2300 – 2400 °C:

- automated analysis of retrospective data on the statistical properties of cooling water flow rate variations;
- analysis of silicon content in pig iron;
- the nose of the air tuyere must be protected with refractory materials, including plasma spraying;
- the inner sleeve of the tuyere must be made of steel plate instead of copper, with additional lining of refractory material;

– cooling water supply mode for the tuyere:

- a) technical water speed up to 11.6 m/s (normal water flow 4 – 5 m/s);
- b) water flow rate 30 m³/h (normal water flow 12 – 16 m³/h);
- c) water pressure 15 atm (normal water pressure 5 – 6 atm).

This regime requires the installation of high-pressure pumps and more robust equipment:

– the tuyere nose thickness should be no less than 40 – 50 mm;

– slag viscosity should not exceed 4 – 5 poise, and the loading of acidic pellets should be avoided.

CONCLUSIONS

It has been determined that the disruption of normal gas distribution and hearth cluttering leads to the formation of a blast furnace deadman, which provokes mass burning of tuyeres and refrigerators.

It is shown that in large-volume blast furnaces, the bubble flow of the gas-coal flow predominates, promoting the growth of the deadman, which can lead to increased accidents involving tuyere devices.

The proposed methodology (mathematical model) allows for the assessment of the maximum temperature of the tuyere zone and the resultant heat flow to the tuyere nose in the presence of a deadman.

Based on the calculated temperature of the tuyere zone, measures are proposed to prevent tuyere burnout depending on the volume of the blast furnace.

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Received 10.08.2023
Revised 17.10.2023
Accepted 11.12.2023

Поступила в редакцию 10.08.2023
После доработки 17.10.2023
Принята к публикации 11.12.2023