Investigation of factors affecting the safety of a blast furnace operation

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Blast furnace air tuyeres are one of the most important elements of the blast furnace design, determining the efficiency of its operation. Formation of "dead man" on the hearth bottom, or in other words, ore-coke sinter is considered as an unfavorable factor affecting the safety of large-volume blast furnaces. The main factors influencing the formation of "dead man" are violation of normal gas distribution and "cooling" of the blast furnace.
This work is devoted to determination of the effluence procedure of the gas-coal flow using the Glinkov criterion. It is shown that a bubble effluent flow prevails in large-volume blast furnaces, i.e. a stable gas zone does not form in front of the tuyere tip. The bubble effluence mode of the gas-coal flow contributes to the growth of "dead man", which, as a result, can lead to an emergence situation.
Prerequisites for burnout of the walls of the tuyeres are created in these conditions, while frequent terminations of the blast furnace operation to replace the tuyeres disorganize the melting technology. The maximal temperature in the tuyere zone has been calculated in this work. It exceeds the theoretical combustion temperature in the blast furnace hearth, what can adversely affect its operation, because the likelihood of an explosion of the blown natural gas will increase.
The resulting heat flow on the tuyere tip was calculated in the work, taking into account the "dead man" formation. This flow exceeds the allowable one, what provokes a massive burnout of the tuyeres and the tuyere cooler.
Key words: blast furnace, tuyere, hearth, "dead man" formation, bubble mode, heat flow, accident, burnout of walls.
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Introduction

Even brief violation of technological process in blast furnace operation is connected with large losses of productivity. Substantial deviations from optimal procedure are often met in the blast durance practice. They lead not only to serious disturbance of blast furnace process, but also to accidents, so creating the conditions which are dangerous for technical staff.

The following typical deviations from normal distribution of gas flow and charge materials can be mentioned: circumferential, axial, channel runs; stockline shift; charge suspension of different kind and degree [1]. It leads to furnace cooling or excessive overheating, overloading of its axial area with mineral charge, violation of run moderation. Non-uniform burnout of profile or stagnation of charge materials with forming of crusts occurs during long-term channel runs. The conditions for blast furnace hearth blocking and burnout of air tuyeres appeared [2].

Not only intensive lining wear and wear use of heat and chemical energy of gases, but also stable hearth blocking with forming of so-called "dead man" can be considered as the most hard consequences of durable circumferential motion of gases. "Dead man" is forming in large-volume furnaces, affects on service life of tuyere connections and can lead to accelerated burnout of tuyeres.

The work is devoted to examination of the effect of "dead man" formation on blast furnace operation, service life of tuyere connections and likelihood of gas explosion, i.e. on operating safety of blast furnace. In was planned, based on calculated relationships, to determine the influence of "dead man" formation on effluent procedure of gas-coal flow from a tuyere tip, as well as to examine operating stability of tuyere connections, variation of resulting heat flow in the hearth and general variations of explosion-hazardous situation in a blast furnace.

"Dead man" is an ore-coke sinter (**Fig. 1**), which is forming on blast furnace bottom as a result of its center cooling.

The following conditions promote formation of "dead man" [3]:

1) charge materials with large amount of fines;

2) low coke strength;

3) insufficient capacity of air blowing remedies with low active axial area.

Hearth blockage by refractory materials (such as vanadium, chromium, titanium etc.) has negative effect on thermal conditions of the furnace operation and requires lowering of ore load. Large amount of graphite is forming in the hearth with decrease of cast iron temperature. The furnace practice is hardly boosted and suspension of burden is observed. Gas motion in the furnace occurs through the narrow peripherical ring or channel, what deteriorates hearth heating. When unprepared material enters the hearth from the axial area, heating is quickly growing weaker. Cold ferriferous slag, which deposits on tuyeres, appears rapidly [4].

Methods and materials.

Two stable hydrodynamic blowing procedures (jet and bubble) are realized in up-to-date blast furnaces.

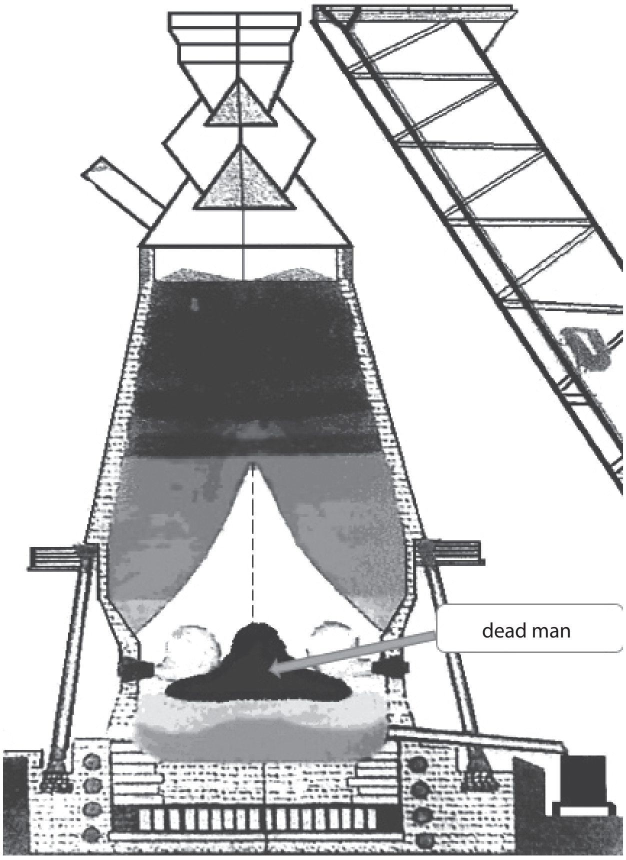

Fig. 1. "Dead man" forming in a blast furnace

The blowing procedure can be determined via Glinkov criterion (G_n), using the formula (1) [4]:

$$G_n = \frac{\rho_g \cdot w_g^2}{\rho_j \cdot g \cdot h_j}; \qquad (1)$$

where ρ_g – efficient flow density, kg/m³;
w_g – speed of gases in the tuyere exit, m/s;
ρ_j – melt density in the tuyere area, kg/m³;
h_j – distance between tuyere axis and belly, m;
g – gravity acceleration, m/s².

Efficient flow density is determined using the formula (2) [5]:

$$\rho_g = Q_a \cdot \rho_{h.b.} + Q_{n.g.} \cdot \rho_{n.g.} + Q_{c.d.} \cdot \rho_{c.d.}; \qquad (2)$$

где Q_a, $Q_{n.g.}$, $Q_{c.d.}$ – volumetric parts «air + oxygen», natural gas and coal dust; $\rho_{h.b.}$, $\rho_{n.g.}$, $\rho_{c.d.}$ – density values of hot blowing, blown-in natural gas and coal dust.

Density of hot blowing is determined via the formula (3) [5]:

$$\rho_{h.b.} = \rho_0 \frac{P \cdot T_0}{P_0 \cdot T_b} \qquad (3)$$

где $\rho_{h.b.}$ – density of hot blowing, kg/m³;
ρ_0 – air density at normal conditions, kg/m³;
P – hot blowing pressure, atm.;
P_0 – atmospheric air pressure, atm.;
T_0 – environment temperature, K;
T_b – blowing temperature, K.

Density of blown-in natural gas is determined via the formula (4) [6]:

$$\rho_{h.b.} = \rho_0^{n.g.} \cdot \frac{P}{P_0} \qquad (4)$$

где $\rho_0^{n.g.}$ – density of natural gas, kg/m³.

If Glinkov criterion is less than 1, the bubble procedure takes place, and if it exceeds 3, there is the jet procedure. Intermediate values are characterized by effluent procedure.

The hearth temperature, where slag is presented in molten or fluid state, is a critical temperature within a blast furnace. Owing to reduction conditions which are caused by presence of coke packing, slag in blast furnace hearth practically does not contain iron oxides and has high melting temperature (1600 K). Thereby, taking into account the required slag overheating, the temperature in the blast furnace hearth shot be not less than 1800 K [7].

Heat transfer of a "dead man" occurs mainly as emission and convection. To calculate the resulting heat flow on the tuyere tip, it is necessary to determine the temperature of the internal blowing area and hydrodynamic conditions of blast furnace blowing [8]. The temperature of the blowing area is corresponding to the temperature of "dead man" surface.

This "dead man" surface temperature T_t can be determined from the thermal balance equation [9] via the formula (5):

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

where T_f – theoretical combustion temperature, ºC;
V_{bost} – gas volume in bosh, mm³/min;
d_h – hearth diameter, m;
B – fuel consumption, kg/t;
T_f – slag fluidity index;
η_{co} – CO content in the furnace center (from a shaft);
d_{proke} – coke diameter in a "dead man", mm.

Slag fluidity index (Tl) is determined using the formula (6) [10]:

$$T_l = T_{l.i.} - \{342 \cdot (CaO/SiO_2) + 11.0 \cdot [(Al_2O_3) + 1.4] + 819\} \quad 6)$$

where $T_{l.i.}$ – liquid iron temperature, ºC;
(CaO/SiO_2) – slag basicity;
(Al_2O_3) – Al_2O_3 concentration in slag, %.

Blowing area, i.e. the area where horizontal gas-liquid flow and reacting zone are situated, is determined via the formula (7) [11]:

$$l_{b.a.} = 5{,}4 \cdot d_0 \left(G_n \cdot \frac{H_0}{d_0} \right)^{0.24}; \qquad (7)$$

where $l_{b.a.}$ - length of blowing area, m;
H_0 – height of liquid bath, m;
d_0 – internal diameter of tuyere tip, m.

Efficient degree of blackness for tuyere edge is determined via the formula (8) [11]:

$$\varepsilon_{ef} = \frac{1}{1 + \left(\frac{1}{\varepsilon_l} - 1\right) \cdot \frac{S}{S_l}}; \qquad (8)$$

where ε_{ef} — efficient degree of blackness for tuyere edge;
ε_l — degree of blackness for tuyere edge (accepted equal to 0.6);
S_1 — square of internal surface of blowing area, m;
S — square of metallic shell ring of tuyere tip, m.

Square of metallic shell ring of tuyere tip S is determined via the formula (9) [12]:

$$S = 0.785 \cdot \left(d_e^2 - d_0^2\right); \qquad (9)$$

where d_e — external diameter of the tuyere tip, m;
d_0 — internal diameter of the tuyere tip, m.

Square of the internal surface of the blowing area S_l is determined via the formula (10) [12]:

$$S_l = \pi \cdot d_e \cdot l_{b.a.}; \qquad (10)$$

where $l_{b.a.}$ - length of blowing area, m.

The resulting heat flow qp on the tuyere edge [13] was determined according to the Stefan–Bolezmann law:

$$q^p = \varepsilon_{ef} \cdot \sigma\,(T_t^4 - T_1^4); \qquad (11)$$

where ε_{ef} — efficient degree of blackness for tuyere edge;
σ — Stefan-Boltzmann constant, equal to $5.67 \cdot 10^{-8}$ Wt/(m^2·K^4);
T_t — temperature of a "dead man" surface, K;
T_1 — temperature of multi=phase flow in tuyere cross-section, K.

The conducted research and analysis of its results

We suggest there is a dense layer between top throat and bosh of the blast furnace; filtration of ascending gases is conducted through this layer. The bubble layer is located in the area between bosh and hearth, while charge material in the bubble layer is in liquid state. Blowing flows include particles of coal dust in addition to air, oxygen and natural gas. Melt drops penetrate in a gas-dust flow only within the range of dual-phase boundary layer behind the reacting zone. The initial data for calculation of Glinkov criterion are presented in the **Table 1**.

Using the formulas (3) and (4), we determine that the values $\rho_{h.b.}$ = 0.61 kg/m^3 and $\rho_{n.g.}$ = 2.08 kg/m^3. Efficient flow density according to the formula (2) is equal to 0.79 kg/m^3, while the value of Glinkov criterion according to the formula (1) makes 0.27, what points on the bubble procedure of effluent of gas-coal flow in the blast furnace [15].

Then we determine the average temperature of "dead man" surface. The initial data for calculation are presented in the **Table 2**.

We calculate the fluidity index T_f = 837 °C according to the formula (6), and the "dead man" surface temperature according to the formula (5) makes T_t = 2331 °C, what exceeds the theoretical combustion temperature by 231 °C.

To calculate the resulting heat flow, which is directed on the tuyere tip of the blast furnace, the following admissions are approved:

1) the blowing area is a cylindrical hollow space with the diameter equals to the external tuyere diameter [16];
2) the "dead man" surface temperature T_t = 2331 °C;
3) the exit tuyere parameters, including multi-phase flow in this cross section, have the temperature T_1=800 °C;
4) the gas flow in the blowing area is filled with coal particles and melt drops, while emission inside it is conducted according to the rules of absolute black body emission.

The initial data for calculation of heat flow towards the tuyere tip are presented in the **Table 3**.

Length of the blowing area is determined via the formula (7), it makes 1.43 m. Efficient blackness degree of a tuyere

Table 1. **Initial data for Glinkov criterion calculation [14]**

Title	Designation	Numerical value
Distance between tuyere axis and belly, m	h_j	5.8
Operating gas speed at the tuyere exit, m/s	w_g	250
Blowing temperature at the tuyere exit, °C	$T_д$	1255
Density of coal dust, kg/m^3	$p_{c.g.}$	1400
Air density, kg/m^3	ρ_0	1.3
Hot blowing pressure, atm	P	2.6
Environment temperature, K	T_0	273
Natural gas density, kg/m^3	$\rho_0^{n.g.}$	0.8
Air pressure, atm	P_0	1
Melt density in the tuyere area, kg/m^3	$p_ж$	3200
Gravity acceleration, m/s^2	g	9.8

Table 2. **Initial data for calculation of the average temperature of "dead man"**

Title	Designation	Numerical value
Theoretic combustion temperature,°C	T_f	2100
Gas volume in the bosh, mm^3/min	V_{bost}	3.7
Hearth diameter, m	d_h	10.85
Fuel consumption, kg/t	B	500
CO content in the furnace center, %	η_{co}	25-34
Cike diameter in the "dead man", mm	d_{proke}	up to 20
Liquid cast iron temperature, °C	$T_{l.i.}$	1250
Slag basicity	(CaO/SiO_2)	2-3
Al_2O_3 concentration in slag, %	(Al_2O_3)	6-10

Table 3. **Initial data for calculation of heat flow towards the tuyere tip**

Title	Designation	Numerical value
Internal diameter of the tuyere tip, m	d_0	0.15
External diameter of the tuyere tip, m	d_H	0.25
Height of the liquid bath, m	H_0	5.8
Blackness degree of the tuyere edge	ε_l	0.6
"Dead man" surface temperature, K	T_t	2573
Temperature of multi-phase flow in the tuyere cross section, K	T_1	1073

edge is calculated via the formula (8) and is equal to 0.953. Square of metallic ring shell of the tuyere tip is determined via the formula (9): $S = 0.033$ m^2, while square of internal surface of the blowing area $S_1 = 1.123$ m^2, according to the formula (10). The resulting heat flow q^p on the tuyere edge is determined via the formula (11) and is equal to 2.3 MWt/m^2.

When operating at stationary conditions (tuyere heating), local contact of the front part with cast iron occurred. The allowable resulting flow to the tuyere edge should not exceed 2.1 MWt/m^2 [17], what testifies that further lowering of water temperature for tuyere cooling is not rational and leads to forming of temperature stresses. It fina-lizes in reducing of service live of the tuyere set and can lead to mass burnout of tuyeres.

Conclusions

As soon as calculated value of Glinkov criterion is less than 1, we can see the bubble effluent procedure of gas-coal flow, i.e. stable gas cavern does not form before a tuyere tip. The combustion area is located in vertical direction, it is extended along the blast furnace axis.

The surface temperature of "dead man" exceeds theoretical combustion temperature in the blast furnace hearth by 231 ºC during blowing-in of coal-dust fuel; it can have negative effect on blast furnace practice, because possibility of gas explosion increases and service life of tuyere connections will be decreased.

It was revealed based on the results of calculation of the resulting heat flow, that lowering of water temperature during tuyeres cooling leads to arising of temperature stresses, provoking so mass burnout of tuyeres and tuyere cooling bed. The bubble effluent procedure of gas-coal flow out of the tuyere tip also can provoke burnout of tuyere connections and tuyere cooling bed, as well as the case when the resulting heat flow exceeds the allowable heat flow towards tuyere tip.

This process promotes rise of hazard of forming of explosion-dangerous situation in large-volume blast furnace, as well as situation when surface temperature of a "dead man" exceeds the combustion temperature.

The research novelty and its practical importance are stipulated by presentation of "dead man" forming and analysis of its following consequences.

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