Burnout resistance assessment of air tuyere in blast furnace

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Abstract. To assess the burn resistance air tuyere in blast furnace using the finite element method (axisymmetric problem), DEFORM-2D software was used. Ceramics with a slurry coating applied to it was used as thermal insulation for protection against air tuyere burnout. The resistance to air tuyere burnout with the selected thermal insulation on its outer surface is estimated by calculating the stress intensity.

1. Introduction
Gas-thermal coatings are known to be used to increase the durability of metallurgical equipment [1–4] and improve the metal products quality [5–8]. Air tuyeres are one of the most important structural elements of a blast furnace determining its performance; failure of the air tuyeres entails the need to stop the furnace to replace the destroyed air tuyeres, which reduces cast iron smelting and increases coke consumption. Burnout is one of the main reasons for the air tuyeres failure, study of which has been the subject of several works [9–12]. Moreover, air tuyeres account for 30 % of all heat losses in the furnace. Therefore, the problem of increasing the air tuyeres resistance and reducing heat loss through their surface is relevant.

Currently, this problem is solved in various ways: by applying gas-thermal coatings and heat-insulating materials with low thermal conductivity to the working surface of the air tuyere [13–16], by lining with refractories from the blow channel side [17–20], etc.

To analyze ways to further increase the tuyeres resistance and reduce heat loss through their surface, it is advisable to simulate their heat and stress state [21–25].

The aim of the work was to assess the tuyere burnout resistance of a blast furnace with the selected thermal insulation during its interaction with molten iron using modern software and stress analysis.

2. Materials and methods
A method for calculating the air tuyere thermal state is known [26, 27]. Stationary thermal conductivity formulas for a flat and cylindrical wall were used in the work [28]. The methodology allows to calculate the heat flux through the air tuyere surface and the temperature distribution in it in a stationary state.

To calculate the of air tuyere heating dynamics, the DEFORM-2D software was used, since the axisymmetric problem needed to be solved [29–32].
The initial data for creating the model was the design of an air tuyere in one of the furnaces at NLMK PJSC (Fig. 1).¹

The air tuyere geometry was drawn in Solid Works and saved in .dxf format. Files with the specified filename suffix were loaded into the Pre-Processor DEFORM-2D and positioned after that. A mesh of 1,000 elements was formed on the air tuyere.

During the calculation in DEFORM-2D, temperature changes of various parts of the air tuyere were observed. According to the calculation results in Post-Processor DEFORM-2D, the Point Tracking function was used to analyze the results. The nodes of the finite element mesh were isolated. For each of the nodes, the temperature of the point (node) was changed over time using DEFORM-2D graphics.

Figure 1. Air tuyere geometry for modeling in DEFORM-2D: 1 – air passage, 2 – water-cooled cavity (a – body, b – tuyere nose), 3 – outer cup, 4 – inner cup, 5 – tuyere nose.

It was assumed that the heat-resistant siliceous fabric glued to the outer surface of the insert would keep it from breaking for some time after cracking occurred while maintaining its performance.

An experiment was conducted at a facility of Severstal, PJSC. There, heat-resistant siliceous fabric was glued both to the entire outer surface of the insert and to its upper part to increase its durability, since the destruction of the insert during the tuyere operation started in its upper part due to the presence of holes for supplying natural gas there.

The operation of the tuyeres at the furnace DP-5 showed that gluing the fabric to the entire length of the insert increases the time of the insert operation before its destruction over than twofold, if compared to cases the fabric was glued to the insert from the flange to the gas supply hole. When tuyeres were installed to the furnace DP-4, while the fabric was glued on the entire surface of the insert, the insert remained operable till the end of the tuyere’s service life, as heat losses through the tuyere during 287 days of operation did not change amounting to 120–130 Mcal/h.

¹ Employees of PJSC NLMK V. N. Titov and A. I. Ternovykh took part in the work
2. Results and discussion
When modeling the thermal and stress state of the air tuyere parts, the following conditions were specified: material – copper; \( t_{\text{blast}} = 1,180^\circ \text{C}; \) \( \alpha_{\text{blast - copper}} = 585 \text{ W/}(\text{m}^2\cdot\text{K}) \); initial temperature – \( 20^\circ \text{C} \). Boundary conditions: medium – surface from the blast channel side; optional: 1 – water-cooled cavity – \( t_{\text{water}} = 43^\circ \text{C} \); \( \alpha_{\text{copper - water}} = 5,815 \text{ W/}(\text{m}^2\cdot\text{K}) \); 2 – tuyere nose surface from the furnace side – \( t = 1,600^\circ \text{C} \); \( \alpha_{\text{medium - tuyere nose}} = 315 \text{ W/}(\text{m}^2\cdot\text{K}) \); 3 – outer cup – \( t = 1,600^\circ \text{C} \); \( \alpha_{\text{medium - outer cup}} = 116 \text{ W/}(\text{m}^2\cdot\text{K}) \).

When calculating the heat transfer coefficients from the hot blast and the furnace hearth, the experimentally obtained average values of heat loss through the body (outer and inner cups) totaled 145,375 W. They were distributed in the ratio of 36 and 46 %, respectively [33], and 139,560 W to the tuyere nose. Heat transfer coefficients from the furnace hearth take into account the air tuyere radiation heating. Radiation from hot blast was neglected. According to the data of [34], the contribution of radiation from the blast stream enriched with oxygen is small, since only water vapor (natural air humidity) is involved in the radiation. In this case, a Cu-Al diffusion coating was taken into account on the air tuyere surface. According to [12], an air tuyere with wall thickness of 5 mm burns out in 1.59 s.

To protect the air tuyeres outer surface from burnout, we were guided by the results of work with a ceramic insert in the blast channel in Severstal PJSC [18]. The application of a slurry coating to ceramics contributed to a decrease in temperature stresses in it due to a temperature decrease and equalization over the insert thickness, and, consequently, an increase in its resistance [19, 20].

Thermophysical and elastic properties of materials are presented in Table 1.

| Properties                        | Copper   | Ceramics | Slurry coating |
|-----------------------------------|----------|----------|---------------|
| Density, kg/m³                   | 8,940    | 3,583    | 3,300         |
| Heat capacity, J/kg*deg           | 390      | 1,291    | 1,300         |
| Thermal conductivity, W/m*deg     | 387      | 8.3      | 7.0           |
| TCLE, {\circ}C⁻¹                 | 1.67⋅10⁻⁵| 6.5⋅10⁻⁶ | 5⋅10⁻⁶        |
| Young’s modulus, MPa              | 1.32⋅10⁵ | 1.46⋅10⁴ | 1.2⋅10⁴       |
| Poisson’s ratio                   | 0.33     | 0.17     | 0.15          |

The thermal insulation length was 150 mm on the outer cup and 100 mm on the tuyere nose to cover the places of the most likely tuyer burnout. In this case, the heat transfer coefficient from the furnace hearth to the thermal insulation was calculated as the weighted average between the corresponding coefficients from the hearth to the outer cup and the tuyere nose, taking into account the thermal insulation length on these parts of the air tuyere: \( \alpha_{\text{medium - insulation}} = 196 \text{ W/}(\text{m}^2\cdot\text{K}) \). The thickness of the ceramics was 8 mm, slurry coating had 3 mm.

The time step was taken equal to 2 s.

When simulating the air tuyere burnout when interacting with molten iron, the contact zone size was 20 mm, the contact place was chosen on the outer cup, and the temperature on the contact surface was 1,500 °C.

Burnout modeling was performed as follows: the boundary conditions were supplemented by a temperature on the air tuyere surface in the of contact area with cast iron (1,500 °C); heat transfer coefficient from molten iron to thermal insulation was taken as \( \alpha_{\text{cast iron - insulation}} = 13,956 \text{ W/}(\text{m}^2\cdot\text{K}) \) [34], and it changed from copper to water from the original \( \alpha_{\text{copper - water}} = 5,815 \text{ W/}(\text{m}^2\cdot\text{K}) \) to 1,163 W/(m²·K) when the temperature on the copper surface from the water side reached 160 °C, as film boiling begins at this temperature, and the probability of air tuyere burnout increases [12].

The time step was taken equal to 0.1 s.
The effect of the considered thermal insulation on the tuyere thermal and stress is presented in Table 2.

**Table 2.** The effect of thermal insulation on the tuyere thermal and stress state

| Parameter calculation location                          | Thermal insulation: ceramics | Thermal insulation: ceramic + slurry coating |
|---------------------------------------------------------|------------------------------|---------------------------------------------|
|                                                         | σ | T   | σ | T   | σ | T   | σ | T   |
| Joint of the outer glass with the tuyere nose           | 72.2 | 102 | 221 | 190 | 72.8 | 98.7 | 114 | 107 |
| Outer cup surface from the water side                   | 7.5  | 90.2 | 223 | 366 | 10.1 | 88.1 | 50.9 | 144 |
| Outer cup surface from the ceramics side                | –   | –   | 207 | 379 | –   | –   | 77.8 | 157 |
| Ceramics surface from the furnace side                  | –   | –   | 99.7 | 1,494 | –   | –   | 60  | 1,068 |
| Slurry coating surface from the furnace side            | –   | –   | –   | –   | –   | –   | 63.7 | 14,88 |

σ is maximum stress intensity, MPa;
T is output temperature in the stationary mode, °C.

A variant of calculating stress intensity with thermal insulation made of ceramics in contact with molten iron is shown in Fig. 2, and that made of ceramics and slurry coating is shown in Fig. 3.

The stress intensity field is displayed in Fig. 2 with an indication of a graph of their changes for four points: P1–P4. The point P1 is in the welded joint area of the tuyere nose and the outer cup, P2 is on the contact surface of the ceramic with molten iron, P3 and P4 are on the external cup in the contact area of the ceramic with molten iron. It can be seen that the stress intensity increases both in the welded joint area due to tight sealing, and the entrance of cast iron due to the temperature difference across the air tuyere structure thickness. In any case, the maximum stress intensity values in ceramics do not exceed the experimental values of the compressive strength for ceramics - 111.7–117.0 MPa. In fact, the maximum stresses in ceramics are lower due to the relaxation phenomenon [35–37].

At the same time, the temperature on the outer cup surface reaches 160 °C after the cast iron entering, i.e., film boiling, for 20 s. If the contact time of cast iron with thermal insulation exceeds 20 s, the tuyere burnout probability increases.
Figure 2. Stress intensity in the part of the outer cup and thermal insulation of ceramics in contact with molten iron.

Similarly, the maximum values of stress intensity in the outer cup do not exceed the yield stress of copper M1 hard alloy under tension — $\sigma_T = 300–450$ MPa [38–40].

The stress intensity field is displayed in Fig. 3 with an indication of a graph of their changes for five points: P1–P5. The point P1 is located in the welded joint area between the tuyere nose and the outer cup, P2 is located on the contact surface of the slurry coating with molten iron, P3 is located on the ceramic in the area of thermal insulation contact with molten iron, and P4 and P5 are located on the outer cup in the area of contact between thermal insulation and molten iron. It can be seen that this thermal insulation option protects the tuyere from burnout more reliably.

Thus, it is recommended to use a ceramic cone with a slurry coating on it as thermal insulation for the outer surface of the air tuyere.
3. Conclusion
To calculate the air tuyere heating dynamics using the finite element method (axisymmetric problem), DEFORM-2D software was used. The choice of thermal insulation for protection against tuyere burnout in blast furnace in the form of a cone made of ceramic with an applied slurry coating is substantiated.

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