Effect of the Step in the Blow Channel of a Blast Furnace Tuyere on Improving Natural Gas Combustion

S D Sayfullayev, D B Efremov and Yu S Tarasov*

The National University of Science and Technology "MISiS", 119991, RF, Moscow, Leninsky prospect, 4, Russia

*trsi@mail.ru

Abstract. The paper demonstrates the effect of the step in the blow channel and the insulating lining on the intensity of mixing natural gas with the air blast and its combustion in the blow channel, as well as on the increase in the air blast temperature at the tuyere outlet. This allows to increase natural gas consumption and reduce coke consumption.

Today’s metallurgical industry development conditions require improving production process at enterprises to solve a number of process and organizational issues [1-22].

The use of natural gas allows reducing coke consumption during cast iron melting, however, as amount of supplied natural gas increases, the natural gas-to-coke replacement ratio decreases. The studies have shown that the value of this ratio for natural gas consumption in the range of 90–100 m$^3$/t and at a theoretical combustion temperature of 2100–2200°C is about 1.0 kg/m$^3$, and for a gas consumption of 180–200 m$^3$/t and combustion temperature of 1900–2000°C decreases by 0.3 kg/m$^3$ [23, 24].

Natural gas utilization efficiency depends substantially on the completeness of its mixing with the air blast. From an energy point of view, the best option for utilizing natural gas in a blast furnace is its incomplete combustion to carbon monoxide and hydrogen under conditions of premixing with oxygen, i.e., when diffusion-kinetic regime of gas combustion is set up. In this case, the number of reducing components in the furnace increases, with the hearth cooling effect dropping to the minimum. For methane-oxygen pre-mixes, the duration of the oxidation reactions is about 3·10$^{-3}$ s, which allows one to expect the end of the combustion of natural gas directly at the tuyere outlet. In this case, an increase in the air blast temperature at the tuyere outlet by 4°C allows increasing natural gas supply by 1 m$^3$ per 1 ton of cast iron. In this case, it is desirable to increase oxygen supply by 1-1.5 m$^3$. Under explosion safety conditions, oxygen concentration in the gas-oxygen mixture of up to 40% at flow rates of 2.5 to 3 m/s and higher is possible [25]. In a conventional tuyere, natural gas is pressed against the blow channel surface by a stream of hot air blast and mixes poorly with it, which leads to incomplete burning of natural gas and its pyrolysis. Therefore, the issue of complete combustion of natural gas is relevant [26].

The main area of addressing this issue is to improve the mixing of natural gas and hot blast, which is done by supplying natural gas through two tubes [27]; installation of a swirler in the blow channel [28] or a sharp change in the blow channel diameter [27]; the effects of acoustic [29] or mechanical [30] vibrations on the natural gas stream. The effective ways to improve the mixing of natural gas and hot blast proved to be its preheating [31] and leading the gas nozzle out into the blow channel [32]. To

![Creative Commons Attribution 3.0 licence](https://creativecommons.org/licenses/by/3.0)
improve the mixing of natural gas and hot blast, a projection was proposed in the insert in the form of a torus portion, located under the nozzle for supplying natural gas symmetrically with respect to it. [32].

In parallel with the issue of more complete combustion of natural gas, an issue of reducing heat losses through tuyere walls is addressed. To solve this issue, thermal insulation of the blow channel is actively used, whose installation involves changing its geometry and the absence of contact of natural gas with the cooled inner copper sleeve, which affects the gas combustion process. [32]. However, the cumulative solution to these issues has not been studied in sufficient detail.

Heat- and wear-resistant gas-thermal and other coatings can be used as thermal insulation [33]. Such technology has been used to increase resistance not only of air tuyeres but also that of other metallurgical equipment [34-36] and to improve the quality of metal products. [37]. In some cases, the diffusion layer consisting of base materials and gas-thermal coating obtained as a result of heat treatment has the required properties [38, 39].

The objective of this paper is to investigate the effect of the blow channel geometry on improving the mixing of natural gas and hot blast, leading to improved combustion of natural gas and increased temperature of the air blast at the tuyere outlet.

Operation of tuyeres showed that the presence of a heat-insulating insert on the blow channel side significantly reduces heat loss, increases the temperature of the air blast at the tuyere outlet, thereby increasing the kinetic energy of the air blast, but with time the thermal stresses the insert breaks down. In this case, the heat losses become higher than the values typical for a structure where the insert is not provided for. This is due to both the increase in the contact surface area between the flow and the blow channel walls, and the intensification of mixing of natural gas with air blast and their burning.

The effect of the blow channel geometry and heat insulating insert on the gas dynamics and heat exchange in the air tuyere of the blast furnace, taking into account the possible combustion of natural gas for four variants of the tuyere design was studied (the tuyere dimensions of one of the NLMK, PJSC’s furnaces were used, with insert used instead of lining):

a) a tuyere without heat insulating insert (basic version);
b) a tuyere with a 13 mm heat-insulating insert and an air gap of 3 mm;
c) a tuyere with a 13 mm heat-insulating insert, an air gap of 3 mm and a step of 11.5 mm;
d) a tuyere with a 27.5 mm step (the previous design version, in which the insert was broken).

The layout of the options under consideration is shown in Figure 1.

![Figure 1. Diagram of different tuyere design options: 1 – blow channel, 2 – water-cooled cavity, 3 – inner sleeve, 4 – nose, 5 – heat insulating insert, 6 – air gap](image)

The study of gas dynamics, combustion, and heat transfer was carried out in Ansys Fluent 15.0.7 medium with the initial data corresponding to the conditions of one of the NLMK, PJSC’s furnaces. The interaction of chemical processes and turbulence is described using the Finite Rate/Eddy dissipation model (in which the ignition occurs only when Arenius kinetics allows it, followed by determining burning intensity by a limiting link of two sequential processes: chemical reaction kinetics and turbulent mixing).
The main modeling results are given in Table 1.

**Table 1.** Comparison of modeling results by options (Figure 1)

| Indicator                              | Option | a*  | b   | c   | d   |
|----------------------------------------|--------|-----|-----|-----|-----|
| Losses through the nose wall, kW      |        | 30.4| 16.2| 17.2| 22.8|
| Losses through the inner sleeve, kW   |        | 55.8| 4.6 | 4.4 | 129.8|
| Total losses through walls, kW        |        | 86.2| 20.8| 21.6| 152.6|
| Heat flow exiting through the blow channel, kW |  | 4534.0 | 4691.8 | 5235.6 | 5877.4 |
| Heat from the combustion reaction, kW  |        | 141.0| 233.8 | 778.6 | 1550.8 |
| Average values of the kinetic energy of turbulence, m²/s² | | 586.2| 567.5 | 726.0 | 1558.0 |
| Average fluid temperature, K          |        | 1286.5 | 1298.8 | 1351.9 | 1431.3 |
| Average fluid temperature at the blow channel outlet, K. | | 1228.9 | 1251.3 | 1356.9 | 1448.5 |

* Note. In the base option, the nose length is 167 mm and the inner sleeve length is 283 mm. In the other options, the nose length is 75 mm, and the inner sleeve length is 375 mm, since the insert was part of the nose portion.

Combustion of natural gas is confirmed by an increase in the average temperature of the fluid, including at the blow channel outlet (table 1) and the concentration of carbon dioxide generated as a result of the natural gas combustion reaction (Figure 2). It follows from Figure 2 that the step in the blow channel has a determining influence on the intensification of natural gas combustion therein.

**Figure 2.** Field of carbon dioxide concentration in half the volume for four design options of the tuyere blow channel: 1–a, 2–b, 3–c, 4–d (Table 1)
Thus, the heat insulating insert and the step in the blow channel, designed for installing the insert, contribute to the beginning and intensification of the combustion of natural gas in the blow channel. Despite the fact that the step in the blow channel has a decisive effect on the intensification of natural gas combustion, the insert is necessary to protect the inner sleeve against burnout due to the temperature increase as a result of the combustion reaction.

The natural gas combustion results were supplemented by those previously obtained by modeling using Excel and in Deform-2D medium [40].

NLMK, PJSC manufactured three tuyeres in which ceramic inserts with a wall thickness of 13 mm were fixed instead of the lining. In this case, the gap between the insert and the copper inner sleeve was 3 mm, and the size of the step between the insert and the nose was 11.5 mm (Fig. 1c). This size of the step in the blow channel was accompanied by increased blast turbulence (table), and thereby by increased heat transfer coefficient on the surface of the tuyere nose and increased cooling water heat loss.

When the insert was destroyed, the step size increased to 27.5 mm (Fig. 1d), the area of the blow channel increased, and cooling water heat losses rose sharply. In addition, as the calculations of temperature fields in the blow channel showed using modeling in the Ansys medium, intensive mixing of natural gas with air blast occurs, and therefore its combustion, which leads to an increase in the temperature of the air blast at the tuyere outlet.

The tuyeres were installed on tuyere apparatus equipped with thermocouples for measuring the temperature of water at the inlet and outlet of the apparatus. Durability of the inserts during the operation of the tuyeres was evaluated by heating water on the tuyere apparatus. It was found that the heating of water on tuyere apparatus with experimental tuyeres decreased on average by 1.6–2.0°C compared to serial tuyeres. The increase in water temperature at the outlet of the tuyere apparatus corresponded to the beginning of the insert disintegration. The durability of inserts was about 3 months.

Despite the fact that the insert protects the inner sleeve against burnout due to burning in the blow channel, heat losses through it increase compared to the option in which there is no step in the blow channel. In addition, the insert’s durability is reduced due to an increase in the temperature gradient during heat cyclings that occur when the furnace is shut down to replace damaged tuyeres.

Conclusion
The effect of the step in the blow channel and the insulating lining on the intensity of mixing natural gas with the air blast and combustion thereof in the blow channel, as well as on the increase in the air blast temperature at the tuyere outlet is demonstrated. This allows increasing the consumption of natural gas and reducing the consumption of coke.

References
[1] Bratan, S., Roshchupkin, S. Synthesis of lunberger stochastic observer for estimation of the grinding operation state (2018) MATEC Web of Conferences, 224, art. № 01133.
[2] Bratan, S., Kolesov, A., Roshchupkin, S., Stadnik, T. Theoretical-probabilistic model of the rotary belt grinding process (2017) MATEC Web of Conferences, 129, art. № 01078
[3] Roshchupkin, S., Kharchenko, A. Method of building dynamic relations, estimating product and grinding circle shape deviations (2018) MATEC Web of Conferences, 224, art. № 01001.
[4] Gerasimova, A.A., Radyuk, A.G., Titlyanov, A.E. Wear-resistant aluminum and chromonickel coatings at the narrow mold walls in continuous-casting machines 2016 Steel in Translation 46(7), c. 458-462
[5] Gorbatyuk, S.M., Pavlov, V.M., Shapoval, A.N., Gorbatyuk, M.S. Experimental use of rotary rolling mills to deform compacts of refractory metals (1998) Metallurgist, 42 (5-6), pp. 178-183. DOI: 10.1007/BF02766359
[6] Radyuk, A.G., Gorbatyuk, S.M., Gerasimova, A.A. Use of electric-arc metallization to recondition the working surfaces of the narrow walls of thick-walled slab molds (2011) Metallurgist, 55 (5-6), pp. 419-423.
[7] Gorbatyuk, S., Kondratenko, V., Sedykh, L. Investigation of the Deep Hole Drill Stability When Using a Steady Rest (2019) Materials Today: Proceedings, 11, pp. 258-264. DOI: 10.1016/j.matpr.2018.12.140

[8] Gorbatyuk, S.M., Morozova, I.G., Naumova, M.G. Reindustrialization principles in the heat treatment of die steels (2017) Steel in Translation, 47 (5), pp. 308-312. DOI: 10.3103/S0967091217050047

[9] Gorbatyuk, S., Kondratenko, V., Sedykh, L. Influence of critical speed when working shafts with symmetrically located monolithic weighting on the accuracy of work surfaces (2019) Materials Today: Proceedings, 19, pp. 2361-2364. DOI: 10.1016/j.matpr.2019.07.695

[10] Gorbatyuk, S., Kondratenko, V., Sedykh, L. Influence of critical speed when working shafts with asymmetrically located monolithic weighting on the accuracy of work surfaces (2019) Materials Today: Proceedings, 19, pp. 2117-2120. DOI: 10.1016/j.matpr.2019.07.222

[11] Karelin, I.N., Sedykh, V.D., Sedykh, L.V. Modernization of a sharply bending elbow in a steel pipeline (2013) Chemical and Petroleum Engineering, 49 (5-6), pp. 351-354. DOI: 10.1007/s10556-013-9754-0

[12] Gorbatyuk, S.M., Pavlov, S.M., Shapoval, A.N., Gorbatyuk, S.M. Experience in application of screw rolling mill for deforming the billets of refractory metals (1998) Metallurg, (5), pp. 32-35.

[13] Gorbatyuk, S.M., Pashkov, A.N., Zarapin, A.Y., Bardovskii, A.D. Development of Hot-Pressing Technology for Production of Aluminum-Based Metal-Matrix Composite Materials (2019) Metallurgist, 62 (11-12), pp. 1261-1266. DOI: 10.1007/s11015-019-00784-01

[14] Zakharov, A.N., Gorbatyuk, S.M., Borisevich, V.G. Modernizing a press for making refractories (2008) Metallurgist, 52 (7-8), pp. 420-423; DOI: 10.1016/s1105-008-9072-5

[15] Keropyan, A.M., Gorbatyuk, S.M., Bibikov, P.Y., Bardovski, A.D. Influence of Roughness of Working Surfaces of the Wheel–Rail System of Open-Pit Locomotives with an Implementable Adhesion Coefficient (2019) Journal of Friction and Wear, 40 (1), pp. 73-79DOI: 10.3103/S1068366619010082

[16] Gorbatyuk, S.M., Sedykh, L.V. Improving the durability of rolling-mill rolls (2010) Metallurgist, 54 (5-6), pp. 299-301. DOI: 10.1007/s11015-010-9297-y

[17] Gorbatyuk, S., Kondratenko, V., Sedykh, L. Tool stability analysis for deep hole drilling (2018) MATEC Web of Conferences, 224, статья № 01035. DOI: 10.1051/matecconf/201822401035

[18] Gorbatyuk, S.M., Kochanov, A.V. Method and equipment for mechanically strengthening the surface of rolling-mill rolls (2012) Metallurgist, 56 (3-4), pp. 279-283

[19] Bast, J., Gorbatyuk, S.M., Kryukov, I.Yu. Horizontal hcc-12000 unit for the continuous casting of semifinished products (2011) Metallurgist, 55 (1-2), pp. 116-118. DOI: 10.1007/s11015-011-9399-1

[20] Gerasimova, A.A., Keropyan, A.M., Girya, A.M. Study of the Wheel–Rail System of Open-Pit Locomotives in Traction Mode (2018) Journal of Machinery Manufacture and Reliability, 47 (1), pp. 35-38. DOI: 10.3103/S1052618818010065

[21] Keropyan, A., Gorbatyuk, S., Gerasimova, A. Tribotechnical Aspects of Wheel-Rail System Interaction (2017) Procedia Engineering, 206, pp. 564-569. DOI: 10.1016/j.proeng.2017.10.517

[22] Keropyan, A.M. Features of interaction of traction wheels of an electric locomotive and a diesel locomotive with rails in the conditions of open mountain works (2016) Journal of Friction and Wear, 37 (1), pp. 78-82. DOI: 10.3103/S1068366616010074

[23] Beresneva, N. G., Kurunov, I. F., Influence of effectiveness of natural gas use in blast furnace performance. Metallurgist. 2009. no. 5, pp. 34-35.(In Russ)

[24] Filatov S.V., Kurunov I.F., Grachev S.N. etc. Blast-furnace production at NLMK: traditions, innovation, development. Chernaya metallurgiya. Byul. in-ta “Chermetinformatsiya”. 2014, no. 10, pp. 30–34. (In Russ.)

[25] Yaroshevskii S.L., Afanas'eva Z.K., Kuzin A.V. etc. Prospects and efficiency of smelting
technology of cast iron in blast furnaces. Novosti nauki Pridneprov’ya. 2010, pp. 25–31. (In Russ.)

[26] Lyalyuk V.P., Donskov E.G., Orel G.I. etc. Increase in efficiency of natural gas use in modern conditions of blast furnace melting. Metallurgicheskie protsessy i oborudovanie. 2006, no. 4(6), pp. 48–50. (In Russ.)

[27] Loginv V.N., Netronin V.I., Shatlov V.A. etc. Vozdushnaya furma domennoi pechi [Air tuyere of blast furnace]. Patent RF no. 2191830. MIIK C21B7/16. Bulleten’ izobretenii. 2002, no. 30. (In Russ.)

[28] Zaitsev Yu.S., Filip’ev O.V., Zaitseva N.N. etc. Furma dlya podachi goryachego dut’ya v domennuyu pech’ [Tuyere for hot blowing in blast furnace]. Patent RF no. 2058399, MIIK C21B7/16. Bulleten’ izobretenii. 1996, no. 11. (In Russ.)

[29] Urbanovich G.I., Urbanovich E.G., Buslaev L.P. etc. Dut’evaya furma domennoi pechi [Blowing tuyere of blast furnace]. Patent RF no. 2164949, MIIK C21B7/16. Bulleten’ izobretenii. 2001, no. 10. (In Russ.)

[30] Loginv V.N., Sukhanov M.Yu., Ukhov A.D. etc. Dut’evaya furma domennoi pechi [Blowing tuyere of blast furnace]. Patent RF no. 2245373, MIIK C21B7/16. Bulleten’ izobretenii. 2005, no. 3. (In Russ.)

[31] Zainullin L.A., Filatov S.V., Kushnarev A.V. etc. Sposob okhlazhdeniya furmy vozdushnogo dut’ya i podachi prirodnogo gaza v domennuyu pech’ [Method of cooling of air blowing tuyere and natural gas supplying to blast furnace and the device for its realization]. Patent RF no. 2449022, MIIK C21B7/16. Bulleten’ izobretenii. 2011, no. 35. (In Russ.)

[32] Levitskii, I.A., Radyuk, A.G., Titlyanov, A.E., Sidorova, T.Y. Influence of the method of natural gas supplying on gas dynamics and heat transfer in air tuyere of blast furnace (2018) Izvestiya Ferrous Metallurgy, 61 (5), pp. 357-363. DOI: 10.17073/0368-0797-2018-5-357-363

[33] Radyuk, A.G., Titlyanov, A.E., Yakoev, A.G., Pedos, S.I. Improvement in service life of blast furnace tuyeres due to gas thermal spraying (2002) Stal’, (6), pp. 11-12.

[34] Gorbatyuk, S.M., Gerasimova, A.A., Radyuk, A.G. Using the coating for the diffusion layer obtaining on the walls of the mold (CCM) (2015) Metallurgical and Mining Industry, 7 (9), pp. 1085-1088.

[35] Gerasimova, A.A., Radyuk, A.G., Titlyanov, A.E. Wear-resistant aluminum and chromonickel coatings at the narrow mold walls in continuous-casting machines (2016) Steel in Translation, 46 (7), pp. 458-462. DOI: 10.3103/S0967091216070068

[36] Radyuk, A.G., Androsov, N.V., Kopylov, A.F., Glebovskij, A.E., Mazurov, V.M., Bokarev, S.P. Mold reconditioning by gas-thermal coating (1998) Stal’, (7), pp. 22-26.

[37] Gerasimova, A.A., Radyuk, A.G., Glukhov, L.M. Applying Coatings to the Narrow Walls of Continuous-Caster Molds to Improve the Quality of the Surface of Slabs (2014) Metallurgist, 58 (5-6), pp. 397-400. DOI: 10.1007/s11015-014-9922-2

[38] Yakoev, A.G., Titlyanov, A.E., Radyuk, A.G., Pedos, S.I. Forming the wear-resistant layers on the surface of copper products (2002) Tsvetnye Metally, (8), pp. 70-73.

[39] Golovanov, A.V., Radyuk, A.G., Slavov, V.I., Baranov, V.P., Titlyanov, A.E., Kul’Mamet’Eva, Yu.Z. Structure and phase composition of the surface layer on steel after alitization (2008) Metal Science and Heat Treatment, 50 (5-6), pp. 300-302. DOI: 10.1007/s11041-008-9039-y

[40] Tarasov, Y.S., Radyuk, A.G., Gorbatyuk, S.M. Effect of the Thermal Insulation of the Inner Wall on the Thermal Condition of the Air Tuyeres of Blast Furnaces (2018) Metallurgist, 61 (9-10), pp. 745-750. DOI: 10.1007/s11015-018-0558-5