Improvement of the smelting efficiency based on the use of composite nozzles in the oxygen lances of high-capacity converters

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Abstract. The nozzle designs of oxygen lances are proposed, which ensure the improvement of technical and economic parameters of converter smelting and metallurgical quality of steel. The developed solutions make it possible to ensure the operation of composite lance nozzles without possible erosion wear of the supercritical part of the nozzle with an acceptable off-design degree. The cylindrical nozzle allows the supersonic flow of oxygen to be stabilized, the length of the initial and transitional sections of the jet to be increased, which is important for organizing a “tough” blowing of the converter bath at the final stage of the operation in order to reduce the oxidation of metal and slag.

1. Introduction
At present, the most widespread in oxygen-converter units with top blowing are multi-jet lances with de Laval nozzles. The lances of this design ensure the achievement of supersonic exhaust velocities, the maximum kinetic energy of the oxygen jet, and the deep penetration of the blowing into the melt. The number of nozzles in the multi-jet lances is of great importance here. In general the number of nozzles is selected taking into account the converter charge, the specific blowing rate and the distance from the level of a calm metal bath to the furnace mouth.

The increase in the number of nozzles (more than six) improves the degree of oxygen absorption and the hydrodynamic situation in the bath of the converter, accelerates the slagging, but leads to the reoxidation of the bath, emissions, a decrease in the yield of liquid steel. With a small number of nozzles (less than five), the “hardness” of the blowing, as a rule, increases, the slagging conditions deteriorate, which leads to an intensive removal of metal from the reaction zone, an increase in the metallization of technological equipment, and a decrease in the yield of liquid steel.

Among scientists and technologists there is no consensus on the optimal or rational number of nozzles and clear quantitative criteria for its determination. In [1, 2] a lance with 9-12 nozzles is recommended for converters with a capacity of 300-400 tonnes at a blowing rate of 5-7 m³/(t·min).

The authors of [3] believe that the number of nozzles in the lances of heavy-duty converters should be at least seven. Lances with 8 – 13 nozzles passed through the industrial testing in units of different capacity; however, having shown good technological results, they had low resistance of the tips because of the complexity of their design and the cooling system of the latter [1 - 5].

2. Theoretical analysis
When calculating and designing the optimal and rational designs of oxygen lances, it is necessary to take into account that in the real operating conditions, in most cases, it is not possible to provide a calculated mode for the gas jets outflow from nozzles of the top of lance [6, 7].

In the design mode of gas outflow from the nozzle, the static pressure at the nozzle exit section \((P_{\text{exit}})\) should be equal to the environmental pressure \((P_{\text{env}})\) at the level of the nozzle into which the outflow occurs. In this case, the off-design degree of the nozzle \(Z = P_{\text{exit}}/R_{\text{env}} = 1\) [8]. Due to the fact that there is no pressure drop at the nozzle exit section \((P_{\text{exit}} - R_{\text{env}} = 0)\), the entire static head pressure of the gas flow after the critical nozzle exit section passes into the high-speed, providing the given dynamic flow pressure to the melt. Thus, the design mode corresponds to a strictly defined value of the degree of nozzle expansion at a given oxygen pressure before the nozzle.

When the pressure of the oxygen jet is greater at the nozzle exit section or less than the ambient pressure on the nozzle, there are cases of off-design gas outflow and the operation of the blowing nozzle. The nozzle operates in the underexpanded mode if the gas pressure at the nozzle exit section exceeds the ambient pressure, i.e. \(P_{\text{exit}} > P_{\text{env}}\) and \(Z > 1\) [9]. In this case, the expansion of the gas to the ambient pressure continues beyond the nozzle, producing compression shocks and depression in the gas flow, and therefore additional energy losses of the jet occur.

At small values of the pressure difference \((P_{\text{exit}} - R_{\text{env}})\), the speed losses due to underexpansion are compensated for by the absence of frictional losses at the end of the nozzle, which allows the length of the supercritical portion of the nozzle to be significantly reduced. If the gas pressure at the nozzle exit section is less than the ambient pressure \((P_{\text{exit}} < P_{\text{env}}\) and \(Z < 1)\), then the nozzle works with overexpansion. At this outflow regime, the boundary layer of the gas jet breaks away from the walls and forms an oblique shock of compression and depression zone inside the nozzle. The latter circumstance is accompanied by entering into the nozzle of high-temperature gases with droplets of metal and slag, which are present in the working space of the unit, which leads to a rapid burn of the nozzle edges, distortion of the velocity diagram in the jet section and burnout of the lance head. Given the wear of the nozzle and the loss of kinetic energy of the flowing jet, the work of the blowing nozzle in the overexpansion mode must be considered inadmissible [6, 7].

In order to improve the stability of the gas flow, the characteristics of the oxygen jets parameters and to prevent changes in the geometry of the blowing nozzle due to the heat, it is recommended [6, 7, 9]:

- to design the blast nozzles in accordance with the design geometry that satisfies the actual state of the oxygen flow ahead of the nozzle and the prescribed oxygen flow rate;
- to prevent erosion wear of the exit section of the nozzle during operation, to design shortened blast nozzles operating in the underexpanded mode with an acceptable off-design degree \((Z\) within \(1.05 - 1.10)\).

For blowing conditions in 350-tonne unit of BOF No. 2 at JSC “Consolidated EVRAZ ZSMK”, a stability improvement of the oxygen jets characteristics that flow from the 4 nozzle top of the lance can be achieved as a result of:

- calculation of a critical nozzle diameter with the upper limit of the oxygen flow rate for blowing the bath (1200 m³/min);
- calculation of the exit diameter of the shortened de Laval nozzles with the lower limit of oxygen flow (700 m³/min);
- supply of the shortened de Laval nozzle with a cylindrical orifice, with the condition of providing the total length of the composite nozzle in the supercritical part (expanding and cylindrical sections) equal to the length of the calculated de Laval nozzle at an oxygen flow rate of 1200 m³/min through the 4 nozzle head (figure 1).

As a result, the operation of composite nozzles of the lance without possible erosion wear of the supercritical portion of the nozzle in the range of oxygen flow rates of 1200-700 m³/min with an allowable degree of inaccuracy is ensured. In this case, the cylindrical nozzle allows the supersonic flow of oxygen to be stabilized, increasing the initial and transitional sections of the jet, which is
important for organizing a “tough” blowing of the converter bath at the final stage of the operation in order to reduce the oxidation of the metal and slag.

3. Results and discussion
For the indicated blowing conditions, the nozzle calculations and the working design of the head of the 4-nozzle oxygen nozzle were performed using the procedure [6, 7] with a modified profile of the supercritical part of the nozzle. The total length of de Laval nozzle with a cylindrical orifice in the supercritical part was 142 mm, including a shortened de Laval nozzle, calculated for the oxygen flow range of 1200 – 700 m³/min, and a cylindrical orifice with a length 58 mm (figure 2).

![Figure 1](image1.png)

**Figure 1.** Design of a top of lance with 4 nozzles and a cylindrical orifice: 1 – connection; 2 – flange; 3 – the insert; 4 – the bowl; 5 – de Laval nozzle with a cylindrical orifice.

![Figure 2](image2.png)

**Figure 2.** Design of de Laval nozzle with a shortened (a) and elongated (b) cylindrical orifice.

Using the developed design of the blowing device in industrial conditions, the tests were conducted. From the analysis of the results (figures 3, 4) obtained during the blowing of the metal melt using a lance with composite nozzles, it is evident that when using de Laval nozzle with a cylindrical
orifice, the oxidation of the slag at an equal carbon concentration in the metal in the turndown (figure 3) is lower than when using a lance with traditional de Laval nozzles.

![Graph](a)

![Graph](b)

**Figure 3.** Dependence of slag oxidation on the concentration of carbon in the metal in the first turndown using traditional (a) de Laval nozzles and (b) with a cylindrical orifice.

Thus, with a carbon content in the metal in the range 0.04 – 0.07%, the minimum value of slag oxidation when using a nozzle with a cylindrical orifice was 22.5%, and with a traditional nozzle 25.4%.

When using nozzles with a cylindrical orifice, some increase in the manganese oxide content in the slag was found at a decrease in the carbon content in the metal (figure 4). At the same time, an increase in oxygen consumption for smelting does not practically affect the oxidation of the slag (figure 5).
Figure 4. Dependence of MnO content in the slag on the concentration of carbon in the metal in the first turndown using traditional (a) de Laval nozzles and (b) with a cylindrical orifice.

Figure 5. Dependence of slag oxidation on oxygen consumption for blowing using traditional de Laval nozzles (a) and with a cylindrical orifice (b).
4. Conclusion
The results analysis of the pilot industrial smeltings using a lance with de Laval nozzles equipped with a cylindrical orifice showed the effectiveness of the developed solution. At the final stage of blowing the use of a composite nozzle allows a “tough” mode of oxygen jet outflow to be organized in order to reduce the slag oxidation, which provides an improvement of technical and economic parameters of converter smelting and the metallurgical quality of steel.

References
[1] Baptizmanskiy V I and Shchedrin G A 1973 Steel 1 20–23
[2] Friedl E and Schmidt G 1972 Ferrous Metals 15 40–45
[3] Mikhailovsky V N 1973 Bulletin “Chermetinformation”. Series 6. Information 4 pp 1–44
[4] Cottedzh D P, Ekols G L et al 1993 Bulletin of NTI “Ferrous Metallurgy” 1(1125) 21–25
[5] Tabata Y, Marsh R C, Kelly P et al 1998 Steelmaking Conference Proceedings pp 451–457
[6] Protopopov E V V et al 2013 Bulletin of Siberian State Industrial University 4(6) 3–7
[7] Feiler S V et al 2016 Bulletin of the Russian Academy of Natural Sciences. West-Siberian Branch 18 pp 111–117
[8] Yavoysky V I et al 1974 Theory of Purging of a Steel-melting Bath (Moscow: Metallugiya) p 495
[9] Gorbik A S et al 1971 Collection of Sci. Works of the Institute VNIPICHERMETENERGOCHISTKA” (Moscow: Metallurgiya) pp 246–253