https://doi.org/10.15407/scine19.04.079

GOLUB, T. S. (https://orcid.org/0000-0001-9269-2953),
MOLCHANOV, L. S. (https://orcid.org/0000-0001-6139-5956),
and SEMYKIN, S. I. (https://orcid.org/0000-0002-7365-2259)

Iron and Steel Institute of Z. I. Nekrasov of National Academy of Sciences of Ukraine,
1, acad. Starodubov square, Dnipro, 49107, Ukraine,
+380 56 790 0514, office.isi@nas.gov.ua

STUDYING THE POSSIBILITY OF USING COHERENT TYPE NOZZLES FOR BOF BLOWING AT THE GAS DYNAMIC SIMULATION STAND

Introduction. *The BOF technology is the leading one in the production of structural steel due to its undeniable advantages.*

Problem Statement. *In the conditions of most Ukrainian converter shops, when the blowing parameters change significantly during the campaign (temperature of the lining, dimensions of the workspace, quality of scrap metal, temperature and composition of iron), and the bath is blown at a constant flow rate with conventional Laval nozzles, sometimes it is impossible to ensure a stable purging process with high rate of post-combustion of CO up to* CO_2*. Therefore, one of the main problems of oxygen conversion is the improvement of the designs of blowing devices, in particular, the nozzles.*

Purpose. *The purpose of this research is to study the possibility of using nozzles of the coherent type for the top oxygen blowing of the converter.*

Material and Methods. *In the research, we have used samples of coherent-design laboratory nozzles having different central part-to-periphery ratio under fixed equal general conditions of jet output (percentage of the annular gap to the total area of the nozzle, %: 75, 65, 50, 45, 35, 25). They have been studied by calculating the jet momentum, through weighing and taking shadow shots when the gas flow velocity reaches 2 M. The results have been compared with those for the cylindrical nozzle.*

Results. *When the gas is supplied at 2 M, the coherent-type nozzles with a fraction of the outer part of 65—75% contribute to the formation of 1.5—1.6 times wider jets as compared with the cylindrical nozzle, with a multinode structure. It helps to increase the jet momentum by 45—55%.*

Conclusions. *The design of a coherent type nozzle with an outer part share of 75% can be recommended to be used as the second tier or the second level nozzles of the top oxygen lance for post-combustion in an oxygen converter due to an increase in the surface area of the jet contact. The efficiency of post-combustion of CO from waste converter gases is expected to increase due to the increasing reaction surface area of additional oxygen jets.*

Keywords: top blowing lance for converter, coherent nozzle, outer annular part of the nozzle, jet weight, geometric parameters of the jet.

Citation: Golub, T. S., Molchanov, L. S., and Semykin, S. I. (2023). Studying the Possibility of Using Coherent Type Nozzles for BOF Blowing at the Gas Dynamic Simulation Stand. *Sci. innov.*, 19(4), 79—92. https://doi.org/10.15407/scine19.04.079

BOF steel production is the most commonly used process for manufacturing structural steel throughout the world. It remains the leading technology due to its undoubted advantages in productivity and liquid steel composition control. According to the experts' forecast, it has all the prerequisites to remain the leading method even with the transition to hydrogen metallurgy [1—5]. According to the statistical report of the World Steel Organization, in 2021, the total production of converter steel was 73.2% of the total [1].

The most urgent task of BOF is to reduce greenhouse gas emissions, in particular CO_2 emissions per ton of finished products. In industrialized regions, steel production is often the largest source of CO_2 emissions [6]. According many authors, the simplest way to solve this problem is to reduce the share of liquid iron, i.e. to increase the share of scrap in the charge [7—10]. For this purpose, one of the solutions is the use of special lance for post-combustion, providing the necessary conditions for a higher degree of oxidation of CO to CO_2 and increasing the heat content of the bath [7, 11, and 15]. At the same time, designing new variants of tips and nozzles for lances, which increase the efficiency of their thermal operation, is a relevant problem. Post-combustion nozzles shall provide jets of sufficient width and length to ensure post-combustion conditions, without reaching the lining of the conical part of the converter. It is known that the nozzles of the second tier of the post-combustion lance are located along the contour of the tip of the blowing lance. The task of the jets flowing from these nozzles is to provide post-combustion in the area under the lance and in the slag. Therefore, the length of the post-combustion jets should be at the level of the working position of the lance (40—60 calibers) [11—14]. When the nozzles for post-combustion are located on the second tier of the blowing lance at a certain height (3—4 m from the first tier), the length of the post-combustion jets is limited by possible burnout of the converter lining in the conical part (20—30 calibers, depending on the capacity of the converter). In particular, the paper presents the results of studying the possibility of using the coherent-type nozzles for the conditions of the top oxygen converter.

The nozzles that create coherent jets have been developed for the EAF process and represent the central nozzle of the main oxygen flow, surrounded by a burning annular layer of the auxiliary gas flow from the circularly arranged nozzles. The authors of [16—17] have found that due to the flame shell, the degree of interaction of the main oxygen flow with the surrounding jet decreases, which reduces the loss of its speed and helps to maintain a greater potential length of the core (the length to which the axial velocity of the jet is equal to the velocity at the exit from the nozzle) of the supersonic jet at a greater distance, unlike an ordinary jet. Coherent jets have been studied by various authors for the conditions of supply of burning fuel of various kinds as a protective layer [16—22]. Blast furnace gas, natural gas, and coke gas have been studied as fuels. The results have shown that the low molecular weight or density of the fuel containment gas increases the potential core length of the main oxygen jet. In [23], the results of a study on the use of compressed air as a protective shell have been presented. Most of the studies have been carried out at subsonic speeds of the auxiliary protective flow. At the same time, the studies for the conditions when supersonic speeds are reached with heated air or oxygen as a protective gas have been conducted as well [24—26]. The flow fields of a coherent jet with the protective structure of a Laval nozzle have been modeled and the influence of the containment Mach number and ambient temperature on the characteristics of a coherent jet with a supersonic protective gas has been studied. Also, many studies have been carried out on numerical simulation of the coherent jets with the use of advanced mathematical tools [24—28].

This study has dealt with the nozzles that create coherent type jets with the main and auxiliary air flows in order to assess the possibility of their use for top blowing in BOF.

In oxygen steelmaking, oxygen flow is supplied at an inlet pressure of approximately 800 to

10 000 kPa through blowing lance nozzles that convert the high inlet pressure energy into the kinetic energy. The blowing nozzle is a specially shaped channel that serves to accelerate the gas to a certain speed and gives the flow a certain direction [29—31]. Using the simplest model, to analyze the gas flow in the nozzle, we have made several assumptions, in which the gas is considered ideal, and the flow is one-dimensional, stationary, and adiabatic. The behavior of the gas jet flowing out of the nozzle can be described by an equation relating the gas flow rate to the cross-sectional area of the outlet channel. Since the mass flow rate of gas is constant in the system, from the law of mass conservation (continuity equation) it follows that [29—31]:

$$Q_m = \rho V S, \tag{1}$$

where ρ, kg/m^3 is the gas density; V, m/s is the velocity of the gas flow; S, m^2 is the surface of outlet area of the nozzle.

Having differentiated both parts of this equation with respect to the spatial coordinate x (m), which is the axis of symmetry of the nozzle, we obtain

$$\frac{1}{\rho}\frac{d\rho}{dx} + \frac{1}{V}\frac{dV}{dx} + \frac{1}{S}\frac{dS}{dx} = 0. \tag{2}$$

Whence the Euler equation follows for the case of a stationary one-dimensional flow

$$V\frac{dV}{dx} = -\frac{1}{\rho}\frac{dP}{dx}, \tag{3}$$

where P, Pa is the gas pressure.

Taking the sound speed from the adiabatic compressibility of matter

$$c^2 = \frac{dP}{d\rho}, \tag{4}$$

where c, m/sis the sound speed, we get

$$V\frac{dV}{dx} = -\frac{1}{\rho}\frac{dP}{d\rho}\frac{d\rho}{dx} = -\frac{c^2}{\rho}\frac{d\rho}{dx}. \tag{5}$$

Denoting the ratio of the local velocity V to the sound speed c as the Mach number

$$M = \frac{V}{c}, \tag{6}$$

(5) can be rewritten as:

$$\frac{1}{\rho}\frac{d\rho}{dx} = -M^2\frac{1}{V}\frac{dV}{dx}. \tag{7}$$

Having eliminated $d\rho$ from formulas (2) and (7), we obtain the final relation:

$$\frac{dS}{S} = \frac{dV}{V}(M^2 - 1). \tag{8}$$

This equation describes the pattern of change in the velocity depending on the cross-sectional area.

The degree of acceleration of the gas flow at the outlet of the nozzle due to the resulting pressure gradient depends on the ratio of the gas pressure at the inlet to the nozzle (P_0, Pa) and the ambient pressure (P_A, Pa). There is a certain critical value of this ratio, at which the gas flow reaches the sound speed in the minimum cross section of the nozzle $c = V\,(1 = \mathrm{M})$ [29—31]:

$$\frac{P_0}{P_A} \geq \frac{(\gamma + 1)^{\frac{\gamma}{\gamma - 1}}}{2} \geq 1.89, \tag{9}$$

where γ is the adiabatic exponent; for a diatomic gas, such as oxygen and air, it is equal to 7/5.

Meeting this condition leads to the fact that the flow becomes supersonic ($1 > M$) and as the distance from the nozzle increases, so does the Mach number M. In this case, shock waves are formed along the jet [26—28, 29, and 30]. The condition of constant pressure along the boundary of the expanding supersonic jet leads to the curvature of this boundary and the formation of compression waves propagating inside the gas mix jet. At the intersection of compression waves, barrel-shaped shock diamonds are formed. In the region of the shock diamonds, there is a sharp decrease in the gas velocity and a corresponding increase in the pressure, temperature, density, and entropy [29—31].

The reflection of this shock occurs with the formation of shock diamonds, the so-called Mach disk, and a reflected shock. The Mach disk is perpendicular to the flow and is the boundary defining the transition from supersonic gas flow velocities back to subsonic. The experimental co-

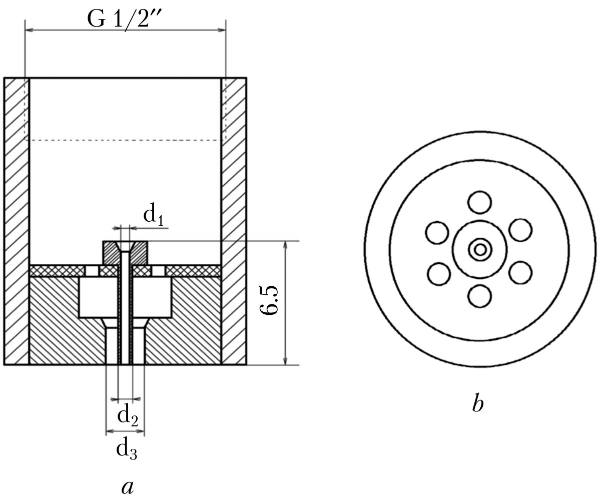

Fig. 1. Schematic representation of an experimental coherent nozzle: *a* — main section; *b* — a top view

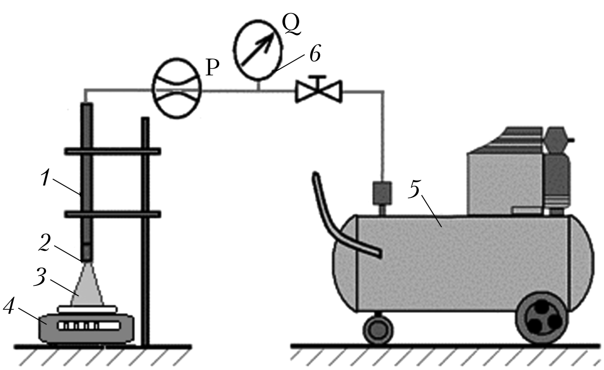

Fig. 2. The device for measuring the weight of the jet: *1* — blowing lance; *2* — experimental tip with the nozzle; *3* — gas jet; *4* — electronic scale; *5* — compressor; *6* — manometer

herent type nozzles are made as cylindrical coaxial structures, the general scheme is shown in Fig. 1. There has been made a series of nozzles differing in the ratio of the central part for main gas flow and the peripheral part for the additional gas flow, under the same general conditions: the outer diameter of the surrounding additional part of the nozzle, the total area of the output section of the nozzles and the same equivalent diameter of the entire coherent type nozzle. Nozzles with a different part of the slotted surrounding part (ring-shaped) in relation to the total output area of the nozzle (75, 65, 50, 45, 35, and 25%) have been studied. The parameters of the nozzles are given in Table 1.

The results of blowing for the coherent-type nozzle prototypes have been compared with those for corresponding cylindrical nozzles with the diameter equal to that of the coherent-type central nozzle.

At the first stage, the weight of the gas jet from experimental nozzles, as an indicator of the momentum, is measured with the electronic scales. Figure 2 shows a photo of the experimental device for studying the weight of the jet at different distances between the nozzle and the weighing plate. For every experiment the nozzle is installed at a fixed distance of 10 to 80 calibers of the diameter of the central main nozzle (or the cylindrical nozzle diameter) with a step of 10 calibers and the jet weight is measured at a different fixed

Table 1. **Experimental Coherent Type Nozzle Parameters**

Central nozzle diameter (d_1), $\times 10^{-3}$ m	Inner diameter of outer annular nozzle part (d_2), $\times 10^{-3}$ m	External diameter of the outer annular nozzle part (d_3), $\times 10^{-3}$ m	% of annular slot part in relation to the total area of the nozzle	Equivalent nozzle diameter, $\times 10^{-3}$ m
1.6	2.0	3.5	75	3.2
1.9	2.4	3.5	65	3.2
2.2	2.6	3.5	50	3.2
2.4	2.7	3.5	45	3.2
2.6	2.9	3.5	35	3.2
2.8	3.1	3.5	25	3.2

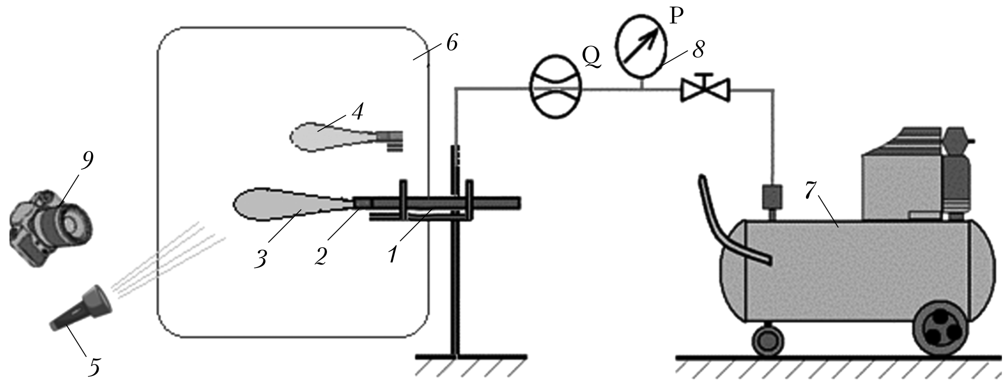

Fig. 3. The device for shadow shooting of the gas jet flowing out of the experimental nozzle to study the geometric parameters of the jet: *1* — blowing nozzle; *2* — experimental tip with a nozzle; *3* — gas-jet; *4* — jetprint; *5* — light source; *6* — whitescreen; *7* — compressor; *8* — manometer; *9* — camera

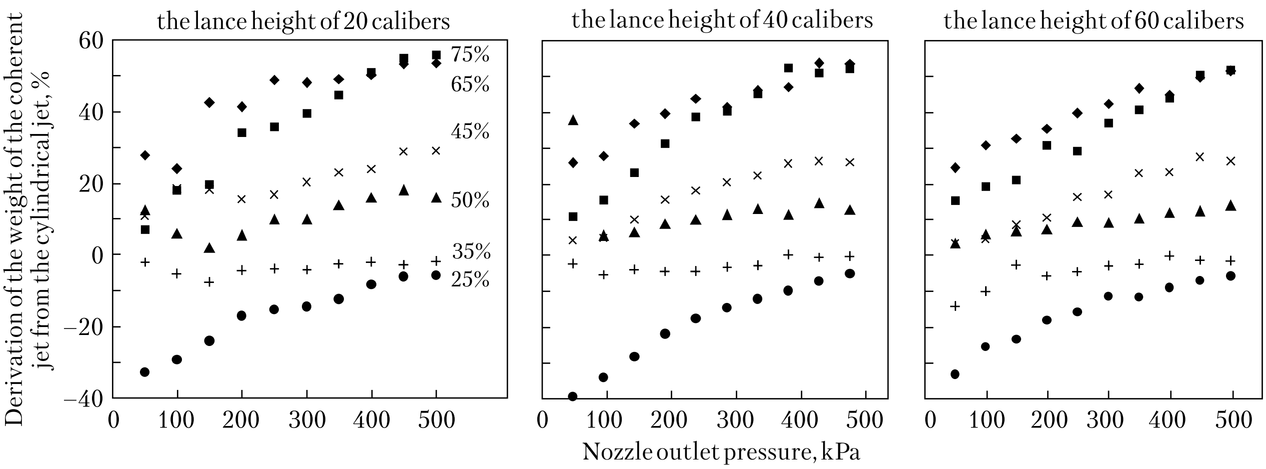

Fig. 4. Deviation of the jet weight of the coherent nozzle from that of the comparative cylindrical nozzle (the data represent a share of the annular slotted part of the coherent-type nozzle in the total area of the nozzle)

pressure of the air flowing through the nozzle (50—500 kPa). At the next stage, the experimental coherent nozzles are studied in comparison with the comparative ones by evaluating the shape and geometric parameters of the flowing jet at a blowing gas pressure that provides conditions similar to the industrial ones (2 Mach).The study is made with the use of adevice for shadow shooting of jets. The shadow shooting device is shown in Fig. 3.

The photographs of the blowing jets flowing from experimental coherent-type nozzles and cylindrical nozzles are obtained at various blowing gas pressure (50—500 kPa). The photographs are taken in total darkness and in the presence of a single point source of light located on one side of the blowing jet. On the other side, there is a white screen, on which, under certain conditions, an image of the jet appears. The nozzle shots are taken at the same position of both the light source and the camera. The comparisons are made in equal conditions for each pair of experimental-comparative nozzles.

The results of weighing the jets of the experimental nozzles have been summarized and compared with the results of weighing the jets of the

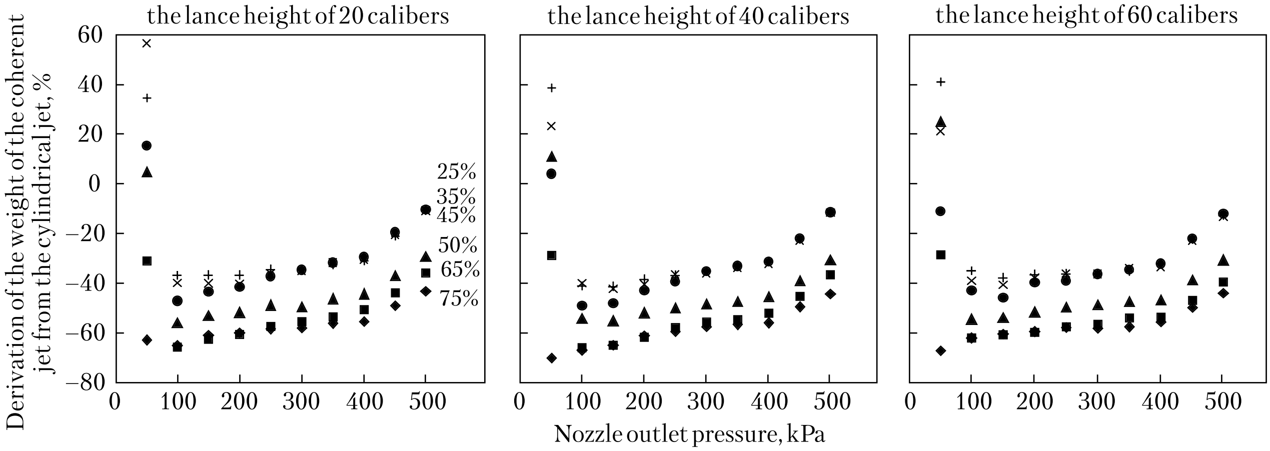

Fig. 5. Deviation of the coherent-type nozzle jet weight from the weight of the jet from the equivalent nozzle (data marked as a share of the annular slotted part of the coherent-type nozzle in relation to the total area of the nozzle)

comparative cylindrical nozzles. Figure 4 shows the deviation of the weight of the jets flowing from the coherent-type nozzles from the weight of the jets flowing from the cylindrical nozzles of the corresponding diameter at each specific position of the lance and the air pressure.

For clarity, the lance positions are chosen corresponding to the common operating modes of the lance position in industrial units of 20—60 nozzle calibers with exposure for the longest period of time at a position of 40 caliber nozzles relative to the level of a still bath. It has been noted that as the pressure applied to the nozzles increases, so does the difference in the weight of the jets, up to a pressure of about 400 kPa (that is about 2 Mach). Then, with increasing pressure, the deviation remains about at the same level. Such behavior is explained by the act that the jets reach supersonic speed (at blowing conditions from 2 to 5 Mach [29—33]). It has been also noted that with an increase in the share of the outer annular slotted part of the nozzle relative to the total area of the coherent-type nozzle, the weight of the coherent jet increases as compared with the case of the comparative nozzles. Moreover, the jets flowing from the nozzles with a share of the outer annular part more than 45% have a positive deviation of the jet weight. It means that the coherent-type jet becomes heavier and stronger, with its momentum increasing as compared with the comparative cylindrical jet at the same pressure of the gas supplied to the blowing and the lance positions. At the same time, the best indicators correspond to the option with a share of the slotted annular part of 65—75% with an increase in the weight of the jet at a gas pressure of 400—500 kPa by 45—55%, while maintaining a similar trend within the working position of the lance. With a share of the outer annular part of 45—50%, the weight gain at 400—500 kPa is 15 and 25%, on average, respectively. At the same time, with a share of the outer annular part of the nozzle of 50%, the increase in the weight of the jet is less than in the case of 45%.

With an area fraction of the outer annular nozzle of 25—35%, on the contrary, the weight of the coherent-type jet decreases in comparison with the comparative nozzles. Moreover, a smaller part of the annular slotted part corresponds to a greater reduction in the weight of the coherent-type jet as compared with the comparative one.

Additionally, the weight of the coherent-type jet corresponding to the equivalent nozzle (diameter 3.2 mm) has been studied. The purpose is to study the effect of transforming a part of the jet into an annular jet under equal blowing gas flow rates. The main results in the form of a deviation of the weight of the coherent-type jet from the weight of the equivalent jet at the working lance height are shown in Fig. 5.

It has been established that if we consider a coherent-type nozzle as a whole nozzle, the transformation of a part of the nozzle into a slot leads to a loss in the weight of the jet. It is probably due to a significant increase in the friction force of the blowing gas and the corresponding energy losses of the jet when passing through a more complex nozzle design. The force of viscous friction depends on the relative speed of the displacement of individual layers of gas. At the same time, the speed of the gas layers decreases towards the pipe walls. In accordance with Newton's equation, the force of friction is equal to [29—31]:

$$F = \eta \cdot S \cdot \frac{\Delta V}{\Delta x}, \qquad (10)$$

where η is the coefficient of viscosity, [Pa · s], S is the area of interaction between the layers of the medium located at a distance of Δx from each other:

$$\Delta x = (d_3 - d_2)/2. \qquad (11)$$

Thus, the closer the nozzle walls are to each other (the smaller Δx) and, accordingly, the longer the edge of the nozzles, which corresponds to the region of reduced flow speed, the greater the frictional force that slows down the overall gas flow along these walls.

The calculation of the edges of the coherent-type nozzles of different studied design and the cylindrical equivalent nozzle have shown (Table 2) that as the share of the outer annular part decreases, the edge length increases and the distance between the parts of the nozzle decreases.

If for the outer annular part of 75%, the length of the nozzle edge becomes 2.2 times longer, then for 25% part of the nozzle the edge length is 2.9 times longer. It has been noted that this effect is observed at a sufficiently high pressure of the blowing gas (more than 50 kPa). At a low pressure of 50 kPa, on the contrary, the weight of the coherent-type jet is greater than the weight of the jet from the equivalent nozzle with the largest deviation at an annular outer part of 35 and 45% (on average by 23 and 38%, respectively). The conditions with a large share of the annular slotted part (65 and 75%), at low pressure of the blowing gas, correspond to a decrease in the weight of the coherent-type jet, as compared with the equivalent. Real industrial oxygen converter blowing is characterized by pressure significantly exceeding 50 kPa and corresponds to 1.5—2.0 Mach. At such blowing gas pressure, converting a part of the nozzle into an additional annular part leads to a reduction in the coherent-type jet weight, as compared with a jet of an equivalent diameter. It has been also noted that a less than 45% decrease in the share of the outer annular part of the nozzle does not lead to any noticeable changes in the weight of the jet.

Table 2. **The Length of the Edge of the Annular Outlet Part of the Experimental Nozzles**

No	Nozzle configuration option	The length of the edge, $\times 10^{-3}$ m	Δx, $\times 10^{-3}$ m
1	Equivalent cylindrical nozzle, diameter 3.2×10^{-3} m	10.05	—
2	Coherent-type nozzle with a share of the outer annular part of 75%	22.29	0.75
3	Coherent-type nozzle with a share of the outer annular part of 65%	24.49	0.55
4	Coherent-type nozzle with a share of the outer annular part of 50%	26.06	0.45
5	Coherent-type nozzle with a share of the outer annular part of 45%	27.00	0.4
6	Coherent-type nozzle with a share of the outer annular part of 35%	28.26	0.3
7	Coherent-type nozzle with a share of the outer annular part of 25%	29.52	0.2

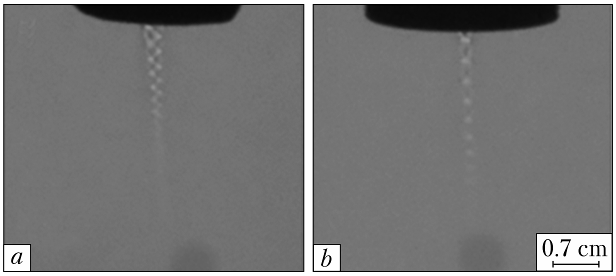

Fig. 6. Photo of a jet flowing from a coherent-type nozzle with an inner diameter of the main nozzle of 1.6×10^{-3} m and a slotted annular part of 75% (*a*) and a jet flowing out of a cylindrical nozzle with a diameter of 1.6×10^{-3} m (*b*)

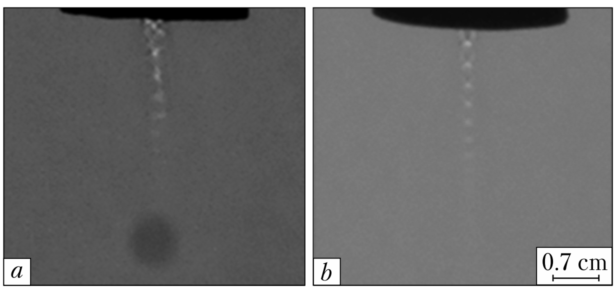

Fig. 7. Photo of a jet flowing out of a coherent-type nozzle with an internal diameter of the main nozzle of 1.9×10^{-3} m and a slotted annular part of 65% (*a*) and a jet flowing out of a cylindrical nozzle with a diameter of 1.9×10^{-3} m (*b*)

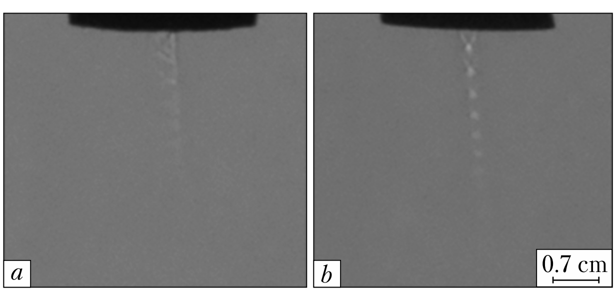

Fig. 8. Photo of a jet flowing out of a coherent-type nozzle with an internal diameter of the main nozzle of 2.2×10^{-3} m and a slotted annular part of 50% (*a*) and a jet flowing out of a cylindrical nozzle with a diameter of 2.2×10^{-3} m (*b*)

Study of geometric jet parameters. The photographs of coherent type jets at a certain pressure, which are obtained at the next stage of the study, have been compared with the photographs of blowing through the comparative cylindrical nozzles with a diameter corresponding to that of the central nozzle. At the exit from the nozzle, the pressure in the jet exceeds atmospheric pressure, and at some distance from the nozzle, the pressure of the supersonic jet decreases to "equalize" with atmospheric pressure. As the distance from the nozzle outlet increases, the gas velocity and the cross section of the supersonic jet increase. In this case, the jet is over expanded and in its widest section the pressure is set below atmospheric pressure. After that, the jet begins to narrow in order to "increase" the pressure and to "equalize" it with atmospheric pressure. The narrowing of the jet leads to deceleration and to the appearance of a "compaction" in some part of the jet cross section, where the velocity slows down to the subsonic one, and the pressure becomes higher than atmospheric, and the whole process is repeated again [29—30]. Figures 6—11 show the comparisons of photo of jets flowing from the coherent-type nozzles and the comparative nozzles of the corresponding diameter obtained under the same blowing conditions (2 Mach). First of all, it has been noted that visual compactions in the jet (characterizing the conditions for the appearance of Mach disks) appear for experimental nozzles at various pressures. In the photo, the compactions are visible as light spots due to the reflection of light rays from them.

So, for the comparative cylindrical nozzles with a diameter of 1.6—2.8 10^{-3} m, the pressure of the appearance of Mach disks is about 170—180 kPa, which corresponds to the previously indicated dependencies [29—30]. For the studied coherent-type nozzles, the pressure at which the first compacted areas appear corresponds to large values and depends on the share of the outer annular part of the nozzle.Figure12 shows the dependence of the Mach disk appearance pressure on the share of the outer annular part of the nozzle.

It has been noted that the dependence has a maximum at a slotted fraction of about 50—65%. At these parameters to reach the conditions At these parameters, to achieve the conditions similar to the industrial ones (for the appearance of Mach disks), a gas supply with a significantly higher pressure is required, namely, about 1.44 times higher as compared with the corresponding comparative nozzles. For other studied parameters of coherent-type nozzles, it is necessary to exceed the pressure 1.05—1.17 times as compared with the corresponding cylindrical nozzles. These values are conditioned by the fact that for the coherent-type nozzles, the total nozzle area is larger than the area of the comparative nozzles, and, accordingly, to achieve a supersonic jet, it is necessary to supply a higher blowing gas pressure to compensate for losses during blowing through coherent nozzles [29—30].

In addition, the obtained extreme nature of the dependence can be explained based on the results of additional studies of the rarefaction created by the outer annular jet. For such experiments, coherent-type nozzles are fabricated with independent gas supplies to each of the parts (the central — the main and outer annular part — the additional flow). The external part of the nozzle is connected to a compressor with a receiver, and the internal part is connected to a pressure gauge capable of measuring vacuum. The device for additional experiments is shown in Fig. 13.

It has established that the jet that flows from the outer annular part of the coherent-type nozzle creates a vacuum in the inner part of the nozzle. The value of this vacuum depends on the share of the outer annular part and has an extreme function with a maximum value of 21 kPa when the share of the outer annular part accounts for 45—50% of the total area of the nozzle (Fig. 14).

The lowest vacuum pressure (5.3 and 10.0 kPa) has been recorded at small shares of the outer annular part of the nozzle (25 and 35% of the total nozzle area, respectively). If the share of the outer annular part is 65 and 75%, the vacuum pressure is slightly lower than at 45—50% and equal to 18 and 16 kPa. Moreover, as the share of the outer annular part increases, the vacuum pressure decreases. The results obtained are in good agreement with the results of measurements of the Mach disk formation pressure for the experimental nozzles.

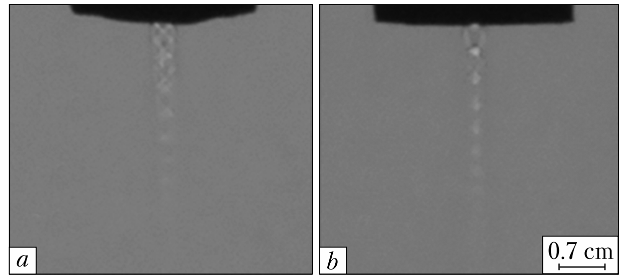

Fig. 9. Photo of a jet flowing out of a coherent-type nozzle with an inner diameter of the main nozzle of 2.4×10^{-3} m and a slotted annular part of 45% (*a*) and a jet flowing out of a cylindrical nozzle with a diameter of 2.4×10^{-3} m (*b*)

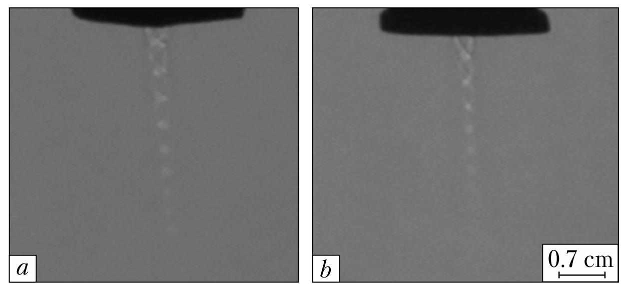

Fig. 10. Photo of a jet flowing out of a coherent nozzle with an inner diameter of the main nozzle of 2.6×10^{-3} m and a slotted annular part of 35% (*a*) and a jet flowing out of a cylindrical nozzle with a diameter of 2.6×10^{-3} m (*b*)

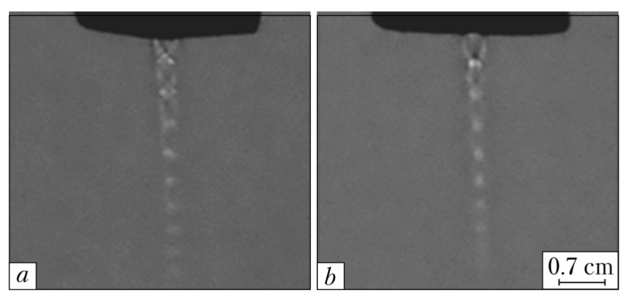

Fig. 11. Photo of a jet flowing out of a coherent nozzle with an internal diameter of the main nozzle of 2.8×10^{-3} m and a slotted annular part of 25% (*a*) and a jet flowing out of a cylindrical nozzle with a diameter of 2.8×10^{-3} m (*b*)

Based on the obtained photos, we have noted the visual differences of the jet from the coherent-type nozzle. The jet flowing out of the cylindrical nozzle is characterized by the braid-like structure: the light areas of jet compaction in the form of rectangular light spots on the photo alternate

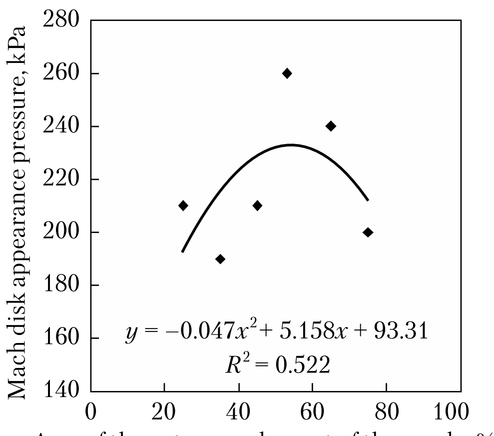

Fig. 12. Dependence of the Mach disk appearance pressure from the share of the slotted annular part in the coherent-type nozzle

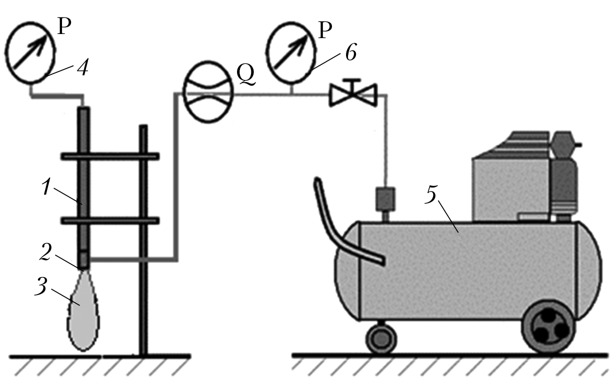

Fig. 13. The device for measuring the vacuum pressure in a jet flow from the coherent-type nozzle: *1* — blowing lance; *2* — experimental tip with nozzle; *3* — gas jet; *4* — manometer measuring the vacuum pressure; *5* — compressor; *6* — manometer indicating the gas pressure applied to the outer part of the nozzle

with the barrel-shaped formations. They appear due to the compressive effect of the environment on the flowing jet. For the coherent jet, a more complex structure is observed, due to the mutual influence of the central and the external annular flows. For the nozzle options with a larger share of the annular slotted part (more than 45% of the total area of the entire nozzle), along the jet, there have been reported the formations alternating in a checkerboard pattern (smaller compaction areas and shorter areas of reduced pressure between them). This nature of the jet causes the above-mentioned increase in the jet pressure as compared with only the cylindrical jet due to a greater number of compactions with smaller gaps between.

At the same time, for a share of annular part of the nozzle of 50%, the least sharp picture has been observed. Probably, in this case, the formed compactions of the central and external flows mutually suppress each other. It manifests itself in the greatest necessary pressure to achieve the conditions for the appearance of Mach disks in this case. At a slotted annular part of 25 and 35%, the overall structure of the jet looks like a pattern of the comparative one. However, in the areas where the cylindrical jet has rectangular (disc-shaped) compactions, for the coherent jet, there are several smaller formations in the form of compactions arranged in a rhombic pattern. This type of jet formation is apparently responsible for the decreasing total weight and consequently, the decreasing jet momentum, as observed during the weighing. The jet compaction section — shock diamond — has a maximum pressure that is the initiator of the further development of the jet advance, i.e. gives it an impulse, and the fragmented section accordingly corresponds to a smaller supply of pressure, which contributes to advancement. The resulting structure is probably caused by the mutual influence of the main and protective external flows with the formation in each of them of compactions due to the mutual superposition of these structures of the main and auxiliary flows instead of isolated Mach disks.

The geometric parameters of the fixed jets have been measured and the results are shown in Table 3 for the blowing gas pressure corresponding to 2 Mach (typical conditions for blowing in industrial units) in the given units i.e. nozzle calibers. It has been found that the jet flowing out of the coherent-type nozzles is wider than the jet flowing out of the comparative cylindrical nozzle by 25.5—68.6% relative to the comparative nozzles of the same diameter (for the cylindrical nozzles, the jet width is an approximate constant and equal to an average of 1.4 nozzle calibers).

What is remarkable: at the same outer diameter of all the studied coherent-type nozzles, the larger the share of the outer annular part of the nozzle, the wider the jet flowing from it by an amount approximately corresponding to the share of the additional part.

The exception is the nozzle with the outer annular part of 50%. For this option, the width increases as little as by 27.9%, as compared with the width of the cylindrical jet. This behavior of the jet is explained by a greater throughput and flow rate passing through the additional component of the nozzle. As a consequence, more air from the medium is drawn into the flow.

As for the length of the jets flowing from the experimental nozzles: it has been noted that for the cylindrical nozzles, the smaller the diameter of the nozzles, the shorter the jet. For the coherent-type nozzles, a decrease in the diameter of the central part does not affect the length of the jet, which is equal to 9.5 calibers, on average. The exception is the nozzle with the outer annular part of 50%, for which the shortest jet length is 6.27 calibers.

Also, it has been noted that that the distance between the Mach disks in the coherent-type jets decreases by 10—21% as compared with the jets flowing from the cylindrical nozzles when the outer part of the nozzle is greater or less than 45—50%. At about 45—50%, the deviation is maximum and accounts for about 30.0—33.3% of the value corresponding to the cylindrical nozzles.

Summarizing the obtained results, the above-established feature of the changing weight of coherent gas jets can be explained by considering in

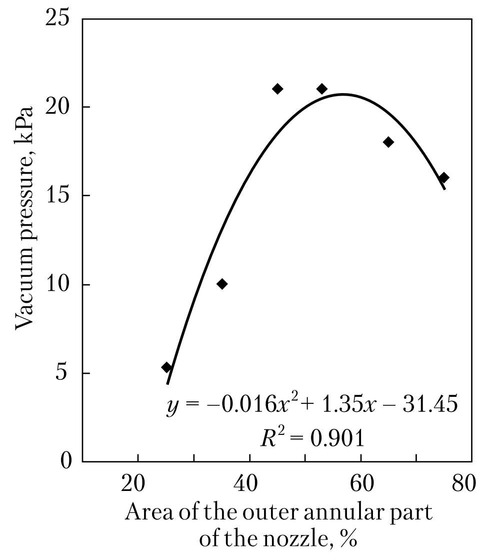

Fig. 14. Vacuum pressure inside the coherent-type nozzle with a different share of the outer annular part of the coherent-type nozzle

Table 3. **Results of Measuring the Geometric Parameters of the Jets Flowing from the Experimental Nozzles(deviation from the comparative nozzles, %)**

No	Diameter of the central part of the coherent-type or the whole cylindrical nozzle, $\times 10^{-3}$ m / the share of the outer part for coherent nozzle	Coherent-type nozzles			Cylindrical nozzles		
		The length of the visible part of the jet, caliber	The jet outlet diameter, caliber	The average distance between Mach disks, caliber	The length of the visible part of the jet, caliber	The jet outlet diameter, caliber	The average distance between Mach disks, caliber
1	1.6/75%	9.25(–32.5)	2.31(+68.6)	1.80(–10.0)	13.70	1.37	2.00
2	1.9/65 %	10.32(–12.2)	2.16(+54.3)	1.23(–18.0)	11.76	1.40	1.50
3	2.2/50 %	6.27(–39.1)	1.88(+27.9)	1.05(–30.0)	10.30	1.47	1.50
4	2.4/45%	9.97(+6.3)	1.92(+37.1)	1.00(–33.3)	9.38	1.40	1.50
5	2.6/35%	9.22(+6.3)	1.81(+26.6)	1.53(–12.6)	8.67	1.43	1.75
6	2.8/25%	9.25(+24.5)	1.77(+25.5)	1.18(–21.9)	7.43	1.41	1.51

detail what happens when the jet exits the coherent nozzle, in the shadow photos. It is known that the gas jet «breaks» when exiting the nozzle due to a significant pressure difference inside and outside the nozzle [29–30]. That is, the geometric dimensions of the jet at the initial stage exceed 1.5—2 times the diameter of the nozzle itself. This process is necessary, because it creates the necessary impulse for the further formation and spread of the jet (cyclic pressure change in the middle of the jet, which, under the conditions of supersonic blowing, leads to the formation of diamonds — Machdiscs). In the case of outflow from the coherent-type nozzles, the central jet shall have conditions for the expansion in the initial section. However, it has been established (see Table 3) that when the central part of the coherent nozzle increases, the diameter of the jet outlet decreases. That is, the jet does not have the opportunity to fully "open", which, in addition to the increased friction, has an additional negative effect on the jet performance.

Thus, based on the results, it can be concluded that:

- the coherent-type jets are characterized by a structure that is quite stable along the length;
- with a smaller share of the outer part of the coherent-type nozzle (25—35% of the total area), there is observed a visually longer jet as compared with the corresponding cylindrical nozzle. In this case, the jet is more like a cylindrical one, but the weight of this jet is less;
- with a larger share of the outer part of the coherent-type nozzle (65—75% of the total nozzle area), there is observed a visually shorter and wider jet with a complex volumetric structure, which contributes to a greater weight of the jet, as compared with the corresponding cylindrical nozzle;
- at the 50% ratio of the outer and inner parts of the coherent-type nozzle, the conditions for the jet formation are most unfavorable.

Therefore, the design of a coherent-type nozzle with a share of an additional part of 75% can be recommended for use as the second circuit or the second tier of the top oxygen lance for post-combustion in oxygen converter. In this case, it is possible to achieve a more efficient post-combustion of exhaust gases due to an increase in the surface area of the jet contact.

ACKNOWLEDGMENTS

The authors would like to thank Prokopenko Pavel, Chief Metrologist of Z. I. Nekrasov Iron and Steel Institute. for the support of experimental works and herewith declare that they have no conflict of interest.

REFERENCES

1. Cappel, J., Ahrenhold, F., Egger, M. W., Hiebler, H., Schenk, J. (2022). 70 Years of LD-Steelmaking — Quo Vadis? *Metals*, 12, 912—936. https://doi.org/10.3390/met12060912
2. Wimmer, G., Apfel, J., Örtelt, P., Mill, H. (2021). Roadmaps to net-zero carbon for the Integrated Plant. *In Proceedings of the 5th ESTADu (30 August — 2 September 2021, Stockholm, Sweden)*.
3. Alshurafa, K., Kleier, T. (2021). Green Primary Steelmaking. *In Proceedings of the Presentation at the AIST Joint Technology Committee* (*29 September 2021, Toledo, OH, USA*).
4. Cavaliere, P., Perrone, A., Silvello, A., Stagnoli, P., Duarte, P. (2022). Integration of Open Slag Bath Furnace with Direct Reduction Reactors for New-Generation Steelmaking. *Metals*, 12(2), 203—225.
5. Suer, J., Ahrenhold, F. (2021). Integration of DRI plants into classical BOF production sites. *In Proceedings of the 5th ESTAD* (*30 August — 2 September 2021, Stockholm, Sweden*).
6. Internal Evaluation. Thyssenkrupp SE Based on Emission Database for Global Atmospheric Research (EDGAR), EDGARv5.0 FT2018. 2020. URL: https://edgar.jrc.ec.europa.eu/ (Last accessed: 18.03.2023).
7. Voraberger, B., Wimmer, G., Salgado, Dieguez, U., Wimmer, E., Pastucha, K., Fleischanderl, A. (2022). Green LD (BOF) Steelmaking — Reduced CO_2 Emissions via Increased Scrap Rate. *Metals*, 12, 466—483. https://doi.org/10.3390/met12030466

8. Wimmer, G., Pastucha, K., Voraberger, B. (2021). Increase of Scrap Rate in Converter Steelmaking. *Steel Tech.*, 15, 28—35.
9. Ryman, Ch., Larsson, M. (2006). Reduction of CO_2 Emissions from Integrated Steelmaking by Optimized Scrap Strategies: Application of Process Integration Models on the BF—BOF System. *ISIJ International*, 46(12), 1752—1758. https://doi.org/10.2355/isijinternational.46.1752
10. Sahoo, M., Sarkar, S., Das, A. C. R., Roy, G. G. (2019). Role of Scrap Recycling for CO_2 Emission Reduction in Steel Plant: A Model Based Approach. *Steel Research International*, 90(8), 1900034. https://doi.org/10.1002/srin.201900034
11. Chernyatevich, A. G., Molchanov, L. S., Sigarev, E. N., Chubin, K. I. (2021). Specific Features of Blowing a Converter Bath with the Application of Modernized Two-Story Oxygen Lances. *Steel in Translation,* 51(8), 538—547. https://doi.org/10.3103/S0967091221080027
12. Valentas, L. S., Straughen, D. T., Bugar, G. S. (2016). BOF post-combustion lances — new advancements and results from four continents. *AISTech 2016 Proceedings* (*16—19 May, 2016, Pittsburgh, Pennsylvania, USA*).
13. Rymarchyk, N. M., Barbus, J. A. (1999). The post combustion lance: theory and application in the BOF steelmaking process. *12th IAS Steelmaking seminar* (*2—5 November, 1999, ISS Argentina*).
14. Rymarchyk, N. M. (1998). Post combustion lances in Basic oxygen furnace (BOF) operations. *Steelmaking conference Proceeding, 1998, 445—449*.
15. Jalkanen, H., Holappa, L.(2014). Treatise on Process Metallurgy. Vol. 3: *Industrial Processes, Chapter 1.4-Converter Steelmaking*, 223—270. https://doi.org/10.1016/B978-0-08-096988-6.00014-6
16. Sarma, B., Mathur, P. C., Selines, R. J., Anderson, J. E. (1998). Fundamental aspects of coherent gas jets. *Electric Furnace Conf. Proc., Iron and Steel Society* (*Louisiana*), 56, 657—72.
17. Zhao, F., Zhu, R., Wang, W. (2019). Characteristics of the Supersonic Combustion Coherent Jet for Electric Arc Furnace Steelmaking. *Materials*, 12, 3504—3518. https://doi.org/10.3390/ma12213504
18. Zhao, F., Zhu, R.,Wang, W. (2020). Characteristics of a coherent jet enshrouded in a supersonic fuel gas. *International Journal of Minerals, Metallurgy and Materials*, 27, 2, 173—180.
19. Malfa, E., Giavani, C., Memoli, F. (2005). Numerical simulation of a supersonic oxygen lance for industrial application in EAFs. *MPT Int*., 28, 44—50.
20. Zhao, F., Sun, D., Zhu, R. (2017). Effect of shrouding gas parameters on characteristics of supersonic coherent jet. *Metall. Mater. Trans. B*., 48, 1807—1816. https://doi.org/10.1007/s11663-017-0931-y
21. Tang, G. W., Chen, Y., Silaen, A. K. (2019). Effects of fuel input on coherent jet length at various ambient temperatures. *Applied Thermal Eng*., 153, 513—523. https://doi.org/10.1016/j.applthermaleng.2019.03.019
22. Tang, G. W., Chen, Y., Silaen, A. K. (2018). Investigation on coherent jet potential core length in an electric arc furnace. *Steel Res. Int*., 90, 1504—1516. https://doi.org/10.1002/srin.201800381
23. Meidani, A. R. N., Isac, M., Richardson, A. (2004). Modelling shrouded supersonic jets in metallurgical reactor vessels. *ISIJ Int*., 44, 1639—1645. https://doi.org/10.2355/isijinternational.44.1639
24. Liu, F., Sun, D., Zhu, R. (2017). Effect of shrouding gas temperature on characteristics of a supersonic jet flow field with a shrouding Laval nozzle structure. *Metall. Mater. Trans. B*., 49, 2050—2062. https://doi.org/10.1007/S11663-018-1272-1
25. Liu, F., Sun, D., Zhu, R. (2019). Effect of shrouding Mach number and ambient temperature on the flow field of coherent jet with shrouding Laval nozzle structure. *Can. Metall. Q*., 58, 96—106. https://doi.org/ 10.1080/00084433.2018.1522815
26. Li, X., Wei, G., Zhu, R., Tian, B., Zhao, R., Lan, X. (2022). Study on the Characteristics of Coherent Supersonic Jet with Superheated Steam. *Metals*, 12, 835—846. https:// doi.org/10.3390/met12050835
27. Hu, S., Zhu, R., Dong, K., Liu, R. (2018). Numerical Simulation and Industrial Experimental Research on the Coherent Jet with "$CH_4 + N_2$" Mixed Fuel Gas. *Metall. Mater. Trans. B*., 49, 2584—2598. https://doi:10.1007/S11663-018-1312-X.
28. Alam, M., Naser, J., Brooks, G., Fontana, A. (2010). Computational Fluid Dynamics Modeling of Supersonic Coherent Jets for Electric Arc Furnace Steelmaking Process. *Metallurgical and Materials Transactions B,* 41(6), 1354—1367. https://doi.org/10.1007/s11663-010-9436-7
29. Kirillin, V. A., Sychev, V. V., Sheidlin, A. Ye. (2008). *Technical thermodynamics*. Moscow [in Russian].
30. Miller, D. R. (1988). *Atomic and Molecular Beam Methods* (Ed. Giacinto Scoles). New York: Oxford University press. P. 14—53.
31. Abramovich, H. N. (1991). *Applied gas dynamics*. Moscow [in Russian].
32. Avduevskiy, V. S., Asharatov, A. A., Ivanov, A. V., Pirumov, U. G. (1985). *Supersonic Nonisobaric Gas Jets*. Moscow [in Russian].
33. Ashkenas, H., Sherman, F. S. (1964). Structure and Utilization of Supersonic Free Jets in Low Density Wind Tunnels. *4th International Symposium on Rare field Gas Dynamics* (July 14—17, 1964, Toronto, Canada). New York. P. 85.

Received 11.10.2022
Revised 08.03.2023
Accepted 22.03.2023

Т.С. Голуб (https://orcid.org/0000-0001-9269-2953),
Л.С. Молчанов (https://orcid.org/0000-0001-6139-5956),
С.І. Семикін (https://orcid.org/0000-0002-7365-2259)

Інститут чорної металургії ім. З.І. Некрасова Національної академії наук України,
пл. акад. Стародубова, 1, Дніпро, 49107, Україна,
+380 56 790 0514, office.isi@nas.gov.ua

ДОСЛІДЖЕННЯ НА ГАЗОДИНАМІЧНИХ МОДЕЛЯХ МОЖЛИВОСТІ ВИКОРИСТАННЯ СОПЕЛ КОГЕРЕНТНОГО ТИПУ ДЛЯ ПРОДУВКИ В УМОВАХ КИСНЕВОГО КОНВЕРТЕРА

Вступ. Технологія кисневого конвертування є провідною для отримання конструкційної сталі завдяки своїм незаперечним перевагам.

Проблематика. В умовах, характерних для більшості конвертерних цехів України, коли вихідні параметри продувки суттєво змінюються в ході кампанії, а продувка ванни проводиться з постійною витратою кисню через звичайну фурму, оснащену наконечником з соплами Лаваля, не завжди вдається забезпечити стабільний процес продувки з високими показниками опалювання вихідних газів CO до CO_2. Тому актуальним у розвитку кисневого конвертування є вдосконалення конструкцій продувних пристроїв (наконечника й сопел).

Мета. Дослідження можливості використання сопел когерентного типу для умов верхньої кисневої продувки у конвертері.

Матеріали та методи. Зразки лабораторних сопел когерентного типу, які відрізняються співвідношенням центральної та периферійної частини при збереженні рівності загальних умов виходу струменя (відсоток кільцевого зазору до загальної площі сопла, % : 75, 65, 50, 45, 35, 25). Їх роботу досліджували шляхом оцінки імпульсу зважуванням на вагах та тіньового фотографування при досягненні швидкості газового потоку на виході з сопла на рівні 2 М. Результати порівнювали з параметрами циліндричних сопел відповідного діаметра.

Результати. При подачі продувного газу на рівні 2 Маха когерентний тип сопел з часткою зовнішньої частини 65—75 % сприяє утворенню більш широких струменів (в 1,5—1,6 рази порівняно з циліндричним соплом), з характерною багато вузловою структурою з короткими проміжками між ними. Він сприяє збільшенню імпульсу струменя на 45—55 %.

Висновки. Визначену конструкцію сопла когерентного типу рекомендовано для використання як другого контуру наконечника або сопел другого ярусу верхньої кисневої фурми, призначених для опалювання відхідних газів в кисневому конверторі. При цьому прогнозовано підвищення ефективності допалювання CO відхідних конвертерних газів через збільшення площі реакційної поверхні додаткових кисневих струменів.

Ключові слова: верхня продувна фурма для конвертера, когерентне сопло, зовнішня кільцева частина сопла, маса струменя, геометричні параметри струменя.