https://doi.org/10.15407/scine20.02.050

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# EVALUATING THE EFFICIENCY OF USING COHERENT-TYPE NOZZLES FOR THE CONDITIONS OF ADDITIONAL POSTCOMBUSTION OF CO TO $CO_2$ IN THE WORKING SPACE OF THE OXYGEN CONVERTER

***Introduction.*** *The requirements for the working conditions of metallurgical industry have been becoming stricter, both in terms of increasing the process indicators and in terms of environmental friendliness of processes.*

***Problem Statement.*** *The main controlling factor of the oxygen-converter process is the oxygen jet supplied through the nozzles of the top lance. The main task of the process is the active mixing for refining and the provision of conditions for the postcombustion of CO to $CO_2$ in off-gases to additionally increase the heat content of the bath in order to enable increasing scrap processing, which improves the environmental friendliness of the process.*

*In electrometallurgy, to solve the problem of deep mixing, it has been proposed to use nozzles of the coherent type (like a cylinder in a cylinder, through which oxidizing and protective gases are supplied).*

***Purpose.*** ***T****o study and to establish the features of using nozzles of the coherent type for the conditions of top oxygen purging in the converter.*

***Materials and Methods.*** *Samples of laboratory nozzles of the coherent type, which differ in the ratio of the central and peripheral parts (75, 50, 25%) with respect to the force of the jet, have been studied with the use of a modified liquid manometer; by two-phase cold modeling; by evaluating the degree of afterburning of CO-containing gases in comparison with the performance parameters of an equivalent cylindrical nozzle.*

***Results.*** *It has been established that the force with which the jet flowing out of the nozzle acts on the liquid is significantly less when that in the case of coherent type nozzles and decreases as the share of the peripheral part of the nozzle increases.*

*According to the results of two-phase cold modeling, it has been noted that the use of coherent type nozzles contributes to the active formation of a foamed emulsion and increases the activity of mixing two-phase liquids during top blowing.*

Citation: Golub, T. S., Molchanov, L.S., Semykin, S. I., and Vakulchuk, V. V. (2024). Evaluating the Efficiency of Using Coherent-Type Nozzles for the Conditions of Additional Postcombustion of CO to $CO_2$ in the Working Space of the Oxygen Converter. *Sci. innov.*, 20(2), 50—59. https://doi.org/10.15407/scine20.02.050

*The use of the coherent-type nozzles with a peripheral part of 75% increases the postcombustion of CO-containing gases by 42.36%.*

***Conclusions.*** *According to the obtained results, it is possible to recommend the use of nozzles of the coherent type to replace the cylindrical nozzles of oxygen lances, which perform the function of additional sources of influence on the bath and for the oxidation of CO in the waste gases.*

*Keywords: top blowing nozzle for the converter, coherent nozzle, outer annular part of the nozzle, power of the jet, mixing of the bath, postcombustion of CO to $CO_2$.*

To date, the experience of operating oxygen converters with top blowing has counted 70 years. During this period, the advantages of this method have been convincingly proven [1]: high productivity and flexibility in the composition of recycled cast iron; simplicity of equipment construction and maintenance in comparison with modern converters of combined blowing. However, this process has some factors that have a negative impact on the environment, in particular, a significant amount of greenhouse gases emitted annually by metallurgical works. And today, we need to urgently focus on this problem.

The main controlling factor responsible for the rate of the decarburization and refining processes and the heat generation indicators of the bath in this process are the parameters of the oxygen jet flowing from the top lance. To create the necessary characteristics of the oxygen jet, the lance is equipped with a tip with nozzles of a certain configuration. For deep penetration into the melt and mixing (the active decarburization), the tip has Laval nozzles at an angle of approximately 10—14 degrees relatively to the lance axis that form the jets with supersonic speed. To solve the task of active slag formation that facilitates the flow of refining processes and protection against intensive dust formation, the cylindrical nozzles of the second tier, placed closer to the edge of the tip, are used. To create the conditions for postcombustion of the outlet gases CO to $CO_2$ and increasing the heat content of the bath, there are used additional cylindrical nozzles through which the jet flows at the speed of sound [2]. The opening angle of such nozzles is 20—30 degrees. There are two options for supplying oxygen to such nozzles: separate supply to the main and additional rows of the nozzles or general supply of oxygen to all nozzles. With skillful use, additional nozzles for postcombustion allow increasing the share of scrap in the charge, which reduces the total output of carbon dioxide per 1 ton of liquid metal product. Their industrial implementation involves the placement of additional cylindrical nozzles both on the tip (double-circuit nozzles) and on an additional tier (two-tier nozzles), or a combination of both options, the three-tier nozzle. The use of tips additionally equipped with cylindrical nozzles for additional burning of CO requires the improvement of the jet mode of converter melting, the latest achievements in this matter have been presented in [3—6].

In electrometallurgical industry, the use of the coherent-type nozzles was proposed to solve the problem of deep mixing of the bath [7—9]. The nozzles of this design have the central part for supplying the main oxygen flow and the annular peripheral part for supplying a protective jet of gas (mainly, methane). The effect of their use is based on the fact that the high-temperature flame formed by the combustion of methane envelops the main supersonic jet of oxygen. As a result, there is created a low-density zone along the main jet, which suppresses the capture effect between the oxygen jet and the surrounding gas and allows the jet to maintain its momentum over a longer distance. It contributes to deeper penetration of the jet into the bath and better mixing of the melt.

Thus, it can be predicted that the use of the coherent-type nozzles contributes to increasing the mass transfer indicators during the top blowing in the oxygen converter. The research presents the results of studying the features of the jet flowing out of a nozzle of a coherent type of different

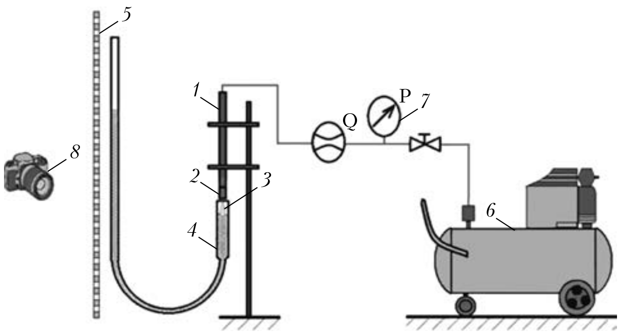


***Fig. 1.*** Scheme of the experimental setup for the study of the force effect of the jet flowing out of nozzles of various configuration: *1* — top lance; *2* — experimental nozzle; *3* — gas jet; *4* — U-tube manometer installation; *5* — ruler; *6* — air compressor; *7* — manometers; *8* — camera

configuration in order to establish the possibility of using them to improve the indicators of the oxygen conversion of the iron-carbon semi-product.

The oxygen-converter process is quite multifactorial and very difficult from the point of view of natural direct research due to extremely high temperature of the melts involved in the process (metal, slag) and gas phase. Therefore, the most common way to study separate links of the process is physical cold modeling [10].

In industrial conditions, the oxygen pressure in front of the nozzle is equal to 1.2—1.4 MPa, which ensures the jet speed at a level of 1.5—2.0 M. There are various methods of physical modeling [10], which differ in a parameter that is selected similar to the industrial option. In this research, it is assumed that the speed of jets flowing out of the experimental nozzles is similar to the industrial one, i.e., there are created the conditions for the blowing gas output under which the jet speed would reach 1.5—2 M. Under these conditions, the jet acquires a structure with periodic zones of compaction (the Mach discs) [11].

The coherent nozzle consists of the main central and the peripheral parts. The ratio of the areas of nozzle parts should create different conditions for the jets to exit and for their resulting action. Therefore, several coherent-type nozzles with a ratio of the peripheral part to the total area of the nozzle of 25, 50, and 75% (with the corresponding diameters of the central nozzles of 2.8, 2.4, and $1.6 \cdot 10^{-3}$ m) have been studied in this research, under the conditions of the equality of the diameter of the nozzle's initial outer part, the total area of the nozzles and, accordingly, at an equivalent diameter of the nozzle of $3.2 \cdot 10^{-3}$ m. The nozzles have been compared with a cylindrical one having an equivalent diameter of $3.2 \cdot 10^{-3}$ m.

The U-tube liquid manometer method has been used to study the force effect of the jet on the liquid [12]. The scheme of the experimental plant is shown in Fig. 1. Compressed air is supplied from the receiver of the compressor with the set pressure to the blowing lance that is equipped with a tip with a test nozzle or a comparative nozzle.

The exit section of the nozzle is located at the inlet section of the liquid manometer at a level of 40 caliber (the height of the lance in the industrial unit at which the main part of the blowing is carried out) of the central nozzle from the liquid. The liquid manometer consists of a plexiglas tube, with the diameter equal to that of the lance, which is connected to a flexible tube of a smaller diameter bent in a U-shape and fixed on a rigid stand. The axes of the lance and the inlet tube of the manometer coincide. The pressure of the blowing jet is applied to the colored liquid in the liquid manometer. At the same time, in a calm state, in the tube of smaller diameter, the liquid level is slightly higher due to the capillary effect (surface tension forces). Under the action of the force ($F$) of the gas jet flowing out of the nozzle, the liquid from the tube of larger diameter is displaced into the tube of smaller diameter, due to which the liquid level in the latter goes up. The force of the jet action ($F$) is calculated by the following equation [12]:

$$F = \frac{\pi \cdot d^2}{4} \ (\rho \cdot g \cdot \Delta h + 2\sigma \left( \frac{1}{R_1} - \frac{1}{R_2} \right), \qquad (1)$$

where $d$ is the inlet diameter of the larger tube of the manometer, ρ and σ are the density and the surface tension of water (the liquid used in the manometer), $\Delta h$ is the difference in liquid levels in the large and the small tubes of the manometer, $R_1$ and $R_2$ are the radiuses of the menisci formed in the larger and in the smaller manometer tubes. The blowing is recorded with the use of a high-speed video camera CASIO EXILIM EX F1, therefore, the radiuses and the difference in the levels of the liquid drop are established when the still frames of the video recording are enlarged. The relative measurement error of $\Delta h$ does not exceed 1.0%.

The two-phase liquid model of converter has been used to study the intensity of mass transfer processes. Water and polymethylsilicone oil (PMS-200) are chosen as model fluids. The main physical properties of model fluids are listed in Table 1. The scheme of the experimental plant is shown in Fig. 2.

30 kg water and 3 kg polymer oil are poured into a transparent vessel to simulate a 10% slag phase. The blowing nozzle is installed at a level of 40 caliber from the surface of the still liquid, equipped with a replaceable nozzle tip, and the air is supplied with the compressor. Blowing is recorded with the use of a high-speed video camera CASIO EXILIM EX F1. To assess the intensity of mixing the bath during blowing, 3 ml Colorex #50 universal dye is injected into the model, and the time, during which the added amount is evenly distributed, coloring the model liquid, is recorded.

To evaluate the effect of the jets flowing out of the experimental nozzles on the efficiency of postcombustion of the outlet gases containing CO (the operating conditions of the upper part, the neck of the converter, where the postcombustion of the outlet gases CO to $CO_2$ are simulated), a physical model has been created (the functional scheme is shown in Fig. 3).The model consists of a 120-liter stainless steel container with a height of 0.69 m

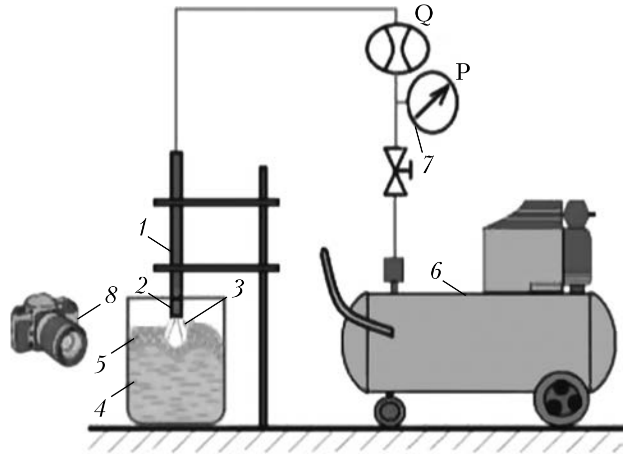


***Fig. 2.*** Functional scheme of the cold two-phase simulation stand: *1* — top lance; *2* — experimental nozzle; *3* — gas jets; *4* — water; *5* — silicone oil; *6* — air compressor; *7* — manometer; *8* — camera

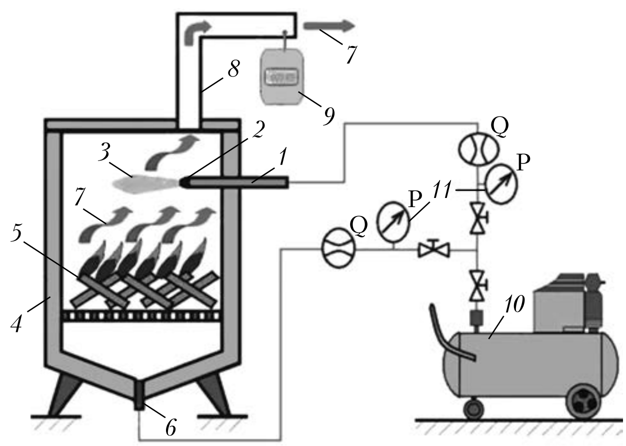


***Fig. 3.*** Functional scheme of the physical model for the study of the postcombustion of outlet gases containing CO: *1* — lance; *2* — experimental nozzle; *3* — blowing gas jet; *4* — working unit; *5* — burning fuel; *6* — bottom nozzle for sustaining combustion; *7* — output gases that contain CO; *8* — metal pipe; *9* — CO measurement sensor Air quality detector E18609; *10* — air compressor; *11* — manometers

*Table 1.* **Properties of Simulated Fluids and Model Fluids**

| Parameter | Metal phase | Slag phase | Water | PMS-200 |
|---|---|---|---|---|
| Density, kg/m³ | 7100—7600 | 3200—4000 | 992 | 968 |
| Viscosity, Pa · s | 0.005 | 0.1—0.3 | 0.0065 | 0.042 |
| Surface tension, kJ/m² | 1200—2000 | 1000—1200 | 79.65 | 33.30 |

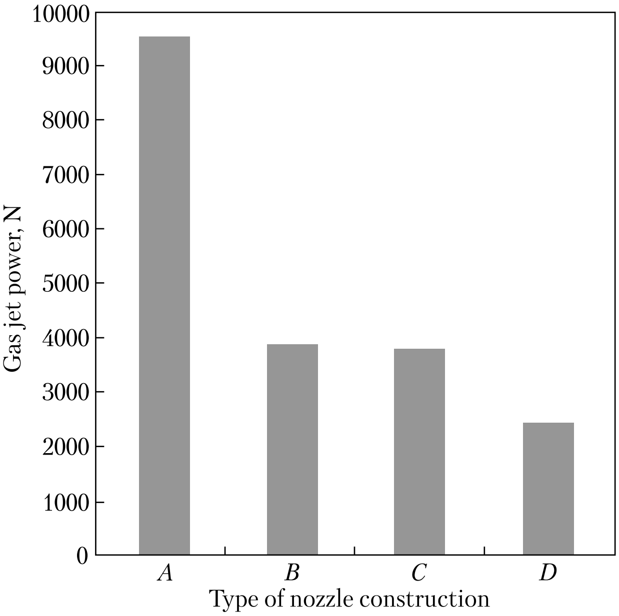


***Fig. 4.*** Comparison of the jet power under the conditions of a flow rate of 2M flowing through comparative nozzle (*A*) and coherent-type nozzle with a different ratio of the peripheral part to the total area of the nozzle (*B* — 25%; *C* — 50%; *D* — 75%)

and a diameter of 0.47 m, which is equipped with a hermetic cover with a metal pipe placed in it for the discharge of outlet gases. The pipe continues with a 3 m corrugated metal hose. At the bottom level of the container, there is placed a metal grid on which burning solid fuel (wood) is supplied, during the burning of which flue outlet gases containing CO and $CO_2$ are formed. The combustion process is supported by supplying air through a bottom nozzle with a diameter of 8 mm and a pressure of 0.7 kPa. In the upper part of the container, perpendicular to the bottom, there is placed a main blowing lance with a test nozzle.

This nozzle location is determined by the need to carry out the postcombustion process of the outlet gases under conditions of blowing with indicators of 2 M without creating a large amount of dust. Blowing is carried out with compressed air, under pressure control. The postcombustion process of waste gases is monitored at the smoke pipe section, with the use of air quality detector E18609 that has 4 digits and measures CO in ppm.

Study of the jet effect on the liquid. The averaged research results calculated by formula (1) are shown in Fig. 4. The conclusion is clear: regardless of the same cross-sectional area of the nozzles and equal relative and coherent flow rates, the separation of the flow into the central and the surrounding ring leads to a significant loss of jet power, which increases as the central part decreases and the peripheral part increases. For example, for the nozzles with 25% peripheral part, the jet power decreases 2.5 times, while for those with a share of the peripheral part of 75% it downs 3.9 times. This is due to the interaction between the main and the peripheral gas flows due to the shock interaction of areas with excess pressure (the Mach discs).

This fact has been considered in more detail in the results of previous studies of the characteristics of the change in the weight of gas jets: because of the existing limitation of the geometric parameters of the coherent nozzle parts and the increasing force of friction experienced by the jet when passing through the complex configuration with a significantly increased contact surface, as compared with the cylindrical nozzle, when the equivalent diameter is kept, while the jet exits the coherent nozzle, the jet does not fully unfold. This leads to a decrease in the possible force of interaction of the jet with the environment.

At this stage, the research is carried out with the use of four nozzle tips with an angle of inclination of the nozzles to the vertical axis of the lance of 12 degrees, which the coherent-type nozzles are equipped with. The share of the peripheral part of the nozzle is 25, 50, and 75% of the total area. The comparison has been made with the four-nozzle tip, with a nozzle diameter of $3.2 \cdot 10^{-3}$ m (equivalent diameter).

The visual observations of the two-phase liquid blowing have shown that the top blowing is accompanied with the formation of a foamy two-layer emulsion on the surface, which consists of small water droplets and gas bubbles of different sizes in oil layer. The submerged part of the gas-liquid jet is formed in the fumigated zone. It captures drops of polymer oil and rising streams of gas bubbles.

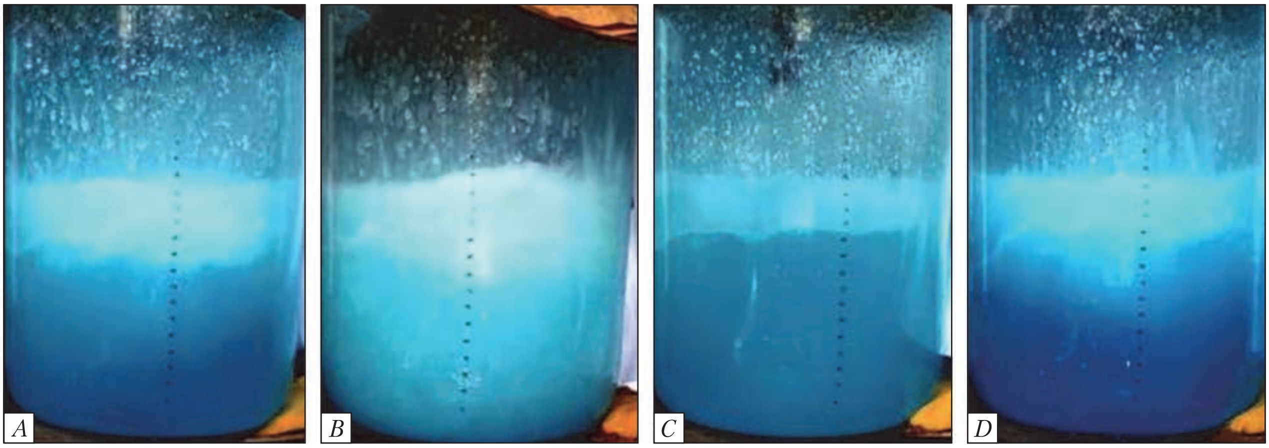


***Fig. 5.*** Comparison of the results of blowing of two phase cold model through comparative nozzle (*A*) and coherent-type nozzle with a different ratio of the peripheral part to the total area of the nozzle (*B* — 25%; *C* — 50%; *D* — 75%)

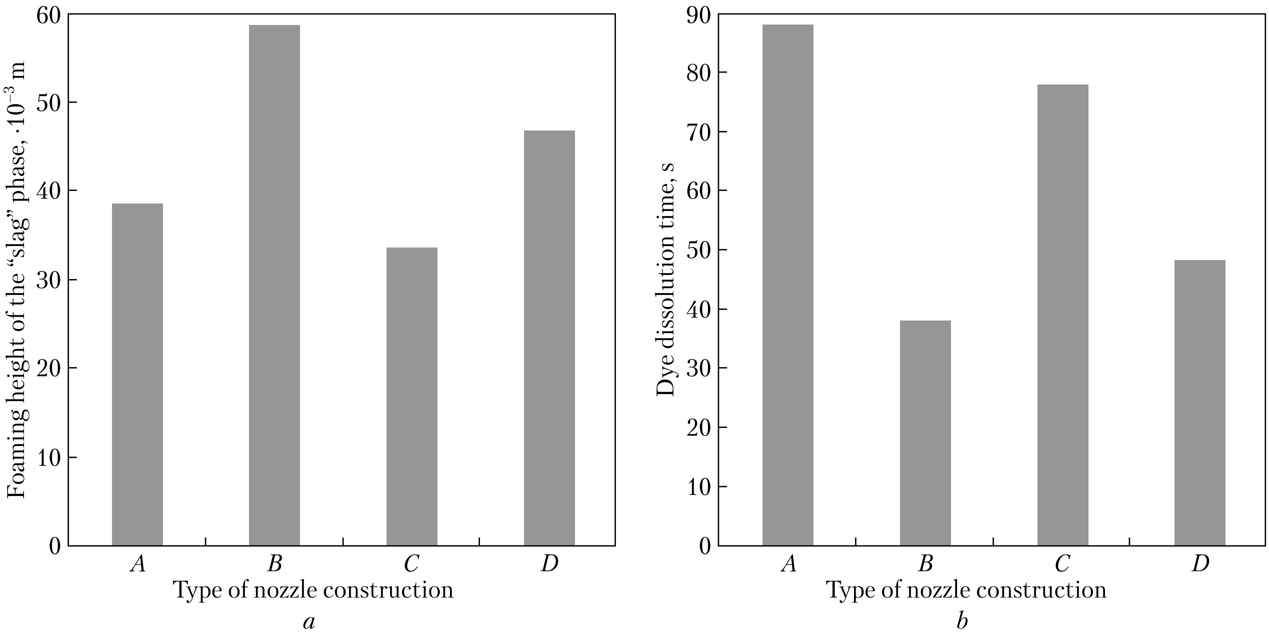


***Fig. 6.*** The results of measuring foaming height of the second — "slag" phase (*a*) and the dissolution time of the dye (*b*) when blowing through a comparative nozzle (*A*) and a coherent type nozzle with a different ratio of the peripheral part to the total area of the nozzle (*B* — 25%; *C* — 50%; *D* — 75%)

Having compared the results of blowing through comparative nozzle (*A*) and coherent-type nozzle with a different ratio of the peripheral part to the total area of the nozzle (25%, *B;* 50% *C;* and 75%, *D*) we find as follows. Figure 5 shows the characteristic photos of blowing through various experimental nozzles in operating conditions (at the same pressure, corresponding to 1.5—2 M). The use of tip *C* does not change the conditions of fluid interaction in the model (see Fig. 5). At the same time, the average height of the formed emulsion on the surface is by 12.5% lower than in the case of comparative tip *A* (Fig. 6, *a*). The dye dissolution time is somewhat shorter (by 11%) than in the case of tip *A* (Fig. 6, *b*).

The use of tips *B* and *D* contributes to the active mixing of the two model liquids. This is especially evident when blowing through tip *B* (see Fig. 5): visually, the jets have the deepest penetration with a greater attraction of the environment to the epicenter of mixing with the formation of a layer of white small particles that reach the bottom of the model (they use about 90% of the bath for the mixing vs. about 60% in the case of using tip *A*). In this option, there has been reported the formation of emulsion on the surface with the highest foaming height 50% more than in option *A*. Blowing through nozzle *D* is also characterized by good foaming of the second-"slag" phase with the formation of emulsion on the surface of small particles (that is, greater interaction of the jet in the surface of the bath) with an emulsion height by 20% higher than in option A (see Fig. 6, *a*). The established features manifest themselves in a significant acceleration of dye dissolution: in the option of blowing with tip *B*, it is 2.3 times faster, while in the option of tip *D*, it is 1.8 times faster as compared with the time of dye dissolution with the use of tip *A* (see Fig. 6, *b*). At the same time, it should be noted that in the case of tip *B*, the dissolution starts from the bottom part of the bath (the dye is quickly drawn to the lower layers of the liquid), whereas in option *D,* it begins from the upper layer of the foamed emulsion.

Based on the above, it is most likely that the specified effect of coherent-type nozzles is achieved due to the complex effect on the two-phase liquid of the jets of the central and slit parts, which makes it possible to grind the drops of water (imitating metal) and to form a more homogeneous emulsion that in industrial conditions can provide a more complete surface contact between the metal and slag phases. Due to this, the efficiency of refining processes in the oxygen converter should increase. The higher level of slag-metal emulsion, the intensive process of its formation, and the more homogeneous structure make it possible to increase the metal yield by reducing the intensity of dust emissions (filtering effect) and the emission of the metal phase drops.

## INFLUENCE ON THE POSTCOMBUSTION OF OUTLET GASES

At this stage, the efficiency of blowing through the coherent-type nozzles with the share of the peripheral part of 25, 50, and 75% has been studied and compared with the case of the cylindrical nozzle with an equivalent diameter of $3.2 \cdot 10^{-3}$ m. For each nozzle, three measurements of CO are made during blowing at a gas pressure that ensures a gas jet flow rate of 1.5—2 M. The average level of CO content for the experimental options of the tips is shown in Fig. 7. It has been found that in the studied conditions, all the options of the coherent-type nozzles contribute to the reduction of the level of CO in the exhaust outlet gases while ensuring the identity of other blowing conditions (i. e, increasing the level of postcombustion of CO to $CO_2$).

Most likely, this is explained by the dispersion of the jet when it is divided into parts and by their interaction both with each other and with the environment. However, the best results in reducing the level of CO have been reported for the use of tip D: the level of CO is by 42.36% lower (and the postcombustion level is respectively higher) as compared with the operation of tip *A* (for the options of tips B and C, the postcombustion level increases by 13.08% and 6.64%, respectively).

It is known from the practice of oxygen-converter production that increasing the level of CO postcombustion in waste outlet gases contributes to increasing the temperature of the bath, which provides the possibility of processing an additional amount of scrap metal [13]. In this way, increasing the yield of usable metal is achieved, and the amount of greenhouse gas emissions per unit of metal products (tons of finished steel) is reduced. Thus, a 40% increase in the degree of post-burning of CO to $CO_2$ can result in growing the amount of scrap in the charge by 12.0 kg/t of steel with corresponding positive consequences.

It is also known [14] that the limitations of the widespread introduction of tips of converter lances with additional nozzles intended for additional combustion of CO are caused by the probability of reoxidation of the final slag and the intensification of the destruction of certain zones on the converter lining. Applying slag garnish to the working surface of the refractories of the converter allows reducing the negative impact of high-temperature torches from postcombustion of CO waste gases on the stability of the lining. Given the fact established by the results of previous studies that the use of coherent nozzles with a peripheral fraction of 75% contributes to the formation of the jets that are shorter than those emanating from similar cylindrical nozzles by approximately 30%, the indicated negative impact on the lining is smaller.

Additional research with the use of liquid metal melts [15] has made it possible to establish that the use of coherent type nozzles of the proposed option allows increasing the degree of oxidation of melt impurities with a 10% reduction in the time they reach correspondingly low concentrations. This may also indirectly indicate a decrease in the oxidation of iron as main component of the melt, which reduces the total amount of slag and, accordingly, its negative impact on heat transfer processes from the postcombustion torch.

The proposed development is envisaged as an improvement of the existing designs of two-level lances in which the cylindrical nozzles are replaced by the coherent nozzle of designed configuration. At the same time, it is recommended to use an angle of 30 degrees, as in the leading structures of multi-tiered lances [4]. The recommended oxygen consumption during blowing is 2.0—2.5 nm$^3$/t min, with a 30-caliber lance working position in the main period of decarburization.

The multi-faceted physical study of the characteristic features of the interaction of gas jets flowing from coherent-type nozzles with liquids and the gas phase in comparison with the blowing through an equivalent nozzle has made it possible to establish the following:

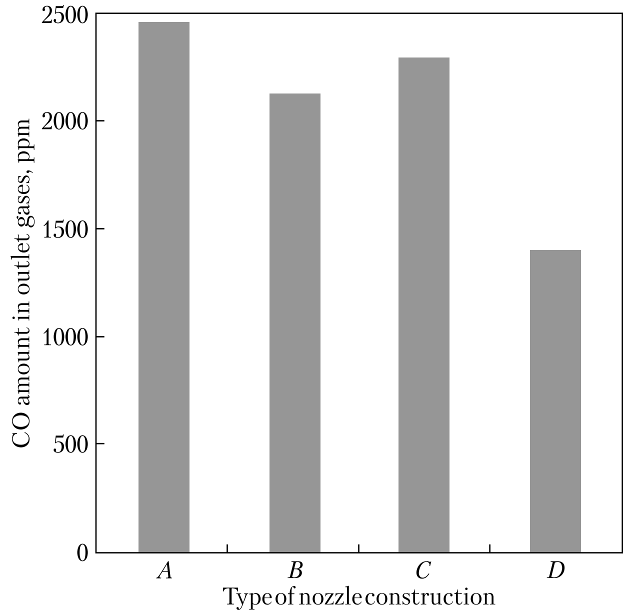


***Fig. 7.*** The amount of CO in the outlet gases for the blowing through comparative nozzle (*A*) and coherent-type nozzle with a different ratio of the peripheral part to the total area of the nozzle (*B* — 25%; *C* — 50%; *D* — 75%)

- the effect of the jet flowing from the nozzle on the liquid significantly decreases when the nozzle is divided into parts with the formation of coherent-type nozzles. Also, it decreases as the share of the peripheral part of the coherent-type nozzle increases;
- the use of nozzles of the coherent type contributes to the active formation of a more homogeneous foamed emulsion on the surface of the bath and increasing the activity of mixing of two-phase liquids during top blowing: for the organization of complete mixing of the two phases while using a nozzle with a share of the peripheral part of 25%, and for the intensification of mixing processes in the upper zone of the unit — with a shareof peripheral part 75%;
- the use of nozzles with equal component areas does not have a positive effect on the exchange processes in the converter bath;
- the use of coherent-type nozzles has a positive effect on the postcombustion process of waste gases that are formed during fuel combustion

and contain CO: a significant 42.36% decrease in the CO amount in the outlet gases and a corresponding increase in the postcombustion in the case of the coherent-type nozzle with a peripheral part of 75%.

Based on the above, it is possible to recommend the use of coherent-type nozzles to replace the cylindrical nozzles of oxygen lances, which perform the function of additional sources of influence on the bath and the additional oxidation of CO in the waste gases. According to [9], a 40% increase in the postcombustion of CO to $CO_2$ can increase the amount of scrap in the charge by 12.0 kg/t of steel with corresponding positive consequences.

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**Received 10.02.2023**
**Revised 20.07.2023**
**Accepted 26.07.2023**

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# ОЦІНКА ЕФЕКТИВНОСТІ ВИКОРИСТАННЯ СОПЕЛ КОГЕРЕНТНОГО ТИПУ ДЛЯ УМОВ ДОПАЛЮВАННЯ СО ДО $CO_2$ У РОБОЧОМУ ПРОСТОРІ КИСНЕВОГО КОНВЕРТЕРА

**Вступ.** Умови роботи металургійної галузі стають все далі жорсткішими, як щодо підвищення технологічних показників, так і з точки зору екологічності процесів.

**Проблематика.** Основним керуючим фактором кисново-конвертерного процесу є кисневий струмінь, що подається крізь сопла верхньої фурми. Завданням процессу є активне перемішування для рафінування й забезпечення умов допалювання вихідних газів СО до $CO_2$ з метою додаткового підвищення тепловмісту ванни для можливості підвищення переробки брухтута збільшення екологічності процесу. В електрометалургії для вирішення завдання глибокого перемішування було запропоновано використання сопел когерентного типу (циліндр в циліндрі, крізь які подаються окислювальний та захисний гази).

**Мета.** Встановлення особливостей при використанні сопел когерентного типу для умов верхньої кисневої продувки у конвертері.

**Матеріали й методи.** Досліджено зразки лабораторних сопел когерентного типу, які відрізняються співвідношенням центральної та периферійної частини (75, 50, 25 %) щодо сили дії струменя за допомогою модифікованого рідинного манометра шляхом двофазного холодного моделювання та шляхом оцінки ступеня допалювання газів, що містять СО порівняно з параметрами роботи еквівалентного циліндричного сопла.

**Результати.** Встановлено, що сила, з якою витікаючий із сопла струмінь діє на рідину, значно менша при використанні сопел когерентного типу та слабшає зі збільшенням долі периферійної частки сопла. За результатами двофазного холодного моделювання відмічено, що застосування сопел когерентного типу сприяє активному формуванню спіненої емульсії та підвищенню активності перемішування двофазних рідин під час продувки зверху. Використання сопел когерентного типу з периферійною частиною 75 % дає збільшення допалювання СО вмісних газів на 42,36 %.

**Висновки.** Відповідно до отриманих результатів рекомендовано використання сопел когерентного типу для заміни циліндричних сопел кисневих фурм, що виконують функцію додаткових джерел впливу на ванну та доокиснення СО у відхідних газах.

*Ключові слова:* верхня форсунка для конвертера, когерентна форсунка, зовнішня кільцева частина форсунки, потужність струменя, змішування ванни, допалювання СО до $CO_2$.