

RESEARCH PAPER

MODELLING THE PROCESS OF OXIDISING IMPURITIES IN A METAL BATH USING COHERENT NOZZLES

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ABSTRACT

The main task of the oxygen-converter process is to produce a liquid metal semi-product with specified properties. It is directly related to the optimization of the blowing mode and devices responsible for the process and technical and economic parameters of melting. This issue is especially relevant for the conditions of converters equipped only with top blowing lance with production-regulated consumption of oxygen as a blowing gas. The effectiveness of the organization of the process of introducing oxygen into the melt, and, accordingly, assimilation by the metal bath basically depends on the design of the lance nozzles. In electrometallurgy, coherent nozzles are used to improve bath mixing performance and activate processes (a central nozzle for supplying oxygen and a peripheral one surrounding it for supplying gas as a fuel that forms an enveloping flame). Therefore, the authors conducted a study of the influence of coherent top nozzles on the oxidation of impurities in the metal bath under the conditions of the use for the oxygen-converter process (with oxygen supplied to both parts of the nozzle).

A high-temperature simulation of the oxidation process of Si from hot metal was carried out by using a Cu-Zn melt (1%) when comparing blowing through a nozzle of a coherent type with a peripheral part of 75% and a conventional nozzle of the equivalent diameter. It was established that oxidation is more intense and the time for the impurity to reach the corresponding low concentrations is reduced (by about 10% compared to blowing through an equivalent nozzle) when a coherent nozzle is used. Additionally, it is possible to predict an increase in technological production parameters by reducing the total blowing time.

Keywords: basic oxygen furnace, top blowing, metal bath, coherent nozzles, impurity oxidation simulation

INTRODUCTION

Steel production processes are based on the oxidation of surplus impurities in the iron-carbon melt. The main oxidizing agent used is gaseous oxygen. The effectiveness of the organization process of its introduction into the melt, and further assimilation by the metal bath essentially depends on the design of the blowing devices, and in particular on the design of the nozzles with which they are equipped [1-3]. Nowadays, the principles of organization of the injection mode are the same for basic oxygen furnace (BOF) converters of different capacities. Therefore, in large-capacity converters with top injection, due to the local placement of the injection, difficulties certainly arise in the organization of metal circulation throughout the volume of the bath and assimilation of the oxygen to the oxidation processes of the main components of the melt [1-4]. This significantly affects the intensity of the flow of converter processes generally.

A couple of decades ago, the technology of coherent jets was introduced in the process of steel production in electric arc furnaces [5-7]. Coherent gas jets are formed by enveloping an ordinary supersonic jet of oxygen with a shell of burning gas. That is, the jet is fed through a nozzle containing a central cylindrical channel for supplying the main flow of gas - oxygen, and a surrounding annular channel for creating a protective flow, mainly of carbon-containing gases (methane, etc.). A flame envelope is created using fuel and an oxidizer. Since the shell the presence, the interaction of the jet with the surrounding gas environment

is reduced, which leads to a greater potential length of the jet core (the section of length up to which the axial velocity of the jet is equal to the velocity at the exit from the nozzle) of the supersonic jet [8-14]. The results of other works also declare that such a gas jet creates fewer splashes than that created by a conventional supersonic jet and increases the level of metal dephosphorization [15, 16].

Considering that the electrometallurgical industry has been using coherent supersonic jets for the past 20 years, the number of research investigating the influence of supersonic coherent jets on oxidation processes in liquid metal is rather limited. For that reason, the aim of this work was to study the influence of an oxygen jet flowing from a coherent nozzle on the oxidation process of constituent impurities of a liquid metal melt.

MATERIAL AND METHODS

A coherent nozzle of a special design (Fig. 1) with a central cylindrical flow of oxygen surrounded by a peripheral annular flow of oxygen with a share of the peripheral part of 75 % was chosen for the study (d_1 and d_2 equal to $1.6 \cdot 10^{-3}$ m and $2.0 \cdot 10^{-3}$ m, respectively, and d_3 was equal to $3.5 \cdot 10^{-3}$ m).

The specified parameters of the nozzle were chosen for research based on the results of previous studies on physical models with water of the force and hydrodynamic characteristics of jets emanating from nozzles of a coherent type with different ratios of

central and peripheral parts [17, 18]. A cylindrical nozzle with an equivalent diameter of $3.2 \cdot 10^{-3}$ m was selected as the comparative nozzle.

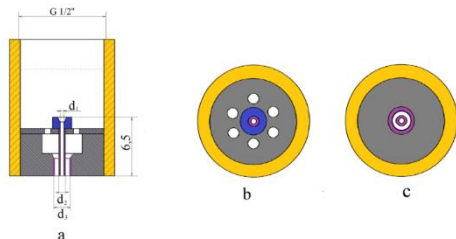


Fig. 1 Schematic representation of an experimental nozzle of the coherent type: a – main section, b – top view, c – bottom view

At the previous stage of research, it was established that at pressure gas 250–400 kPa the use of coherent-type nozzles allows for increasing the force of the jets flowing out on the liquid by up to 74% (relative) in a case of a share of the peripheral part of 75% in relation to the total area of the nozzle in comparison with blowing through a cylindrical nozzle [17]. An increase in the power of the jet is demonstrated in an increase in the penetration depth of the jet into the liquid, which affects the possibility of an oxidation reaction.

Gibbs energy (ΔG) was used to estimate the probability of chemical reactions, which was calculated using the formula [19]:

$$\Delta G = -RT \ln K_p + RT \cdot \Sigma k \cdot \ln P \quad (1)$$

where R – universal gas constant, 8,314 J/mol·K; T – temperature of the bath, K; K_p – equilibrium constant, which has an established dependence on temperature for each reaction [19]; k – is the number of moles of gaseous substances; P – excess pressure acting on the system, Pa.

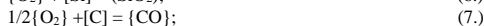
The excess pressure was calculated taking into account the depth of penetration of the oxygen streams that flowed from the nozzles of the developed design and comparative nozzles, respectively, and which was calculated using the empirical expression from [20]:

$$L = 0,723 \sqrt{\left(\frac{Q_{pg}}{0,95nd\rho_{me}}\right)^2 (1 - 0,04 \sqrt{\frac{h_l}{d'}} (\cos \alpha))} \quad (2)$$

where Q – blowing gas consumption, m^3/min ; ρ_g and ρ_{me} – densities of gas and metal, respectively, kg/m^3 ; n – number of nozzles, piece; d and d' – diameter of nozzles and reduced diameter of nozzles (taking into account the total area of all nozzles), m; h_l – the position of the lance relative to the metal melt, m; α – angle of inclination of the nozzles to the axis of the lance, degrees.

The consumption of blowing gas and the position of the nozzle were determined by the method of conducting research on the proposed type of nozzles and were 0.032 m^3/min and 40 calibers of the blowing nozzle, respectively.

The chemical reactions that can occur in the primary reaction zone when the top blowing of metal bath with oxygen were analyzed:



The estimation of the Gibbs energy parameter for the specified reactions was carried out by comparing the performance indicators of the experimental and comparative nozzles. The evaluation result is shown in **Figure 2**.

It was established that the value of the Gibbs energy is more negative when using a coherent nozzle for the indicated reactions. Consequently, the probability of reactions in the primary reaction zone is greater compared to the option of using standard nozzles. This is due to the greater depth of penetration of the jet that flows from the nozzle of the coherent type, which contributes to better absorption of oxygen by the bath and its distribution to the oxidation reactions. At the same time, the largest difference in the calculated values was determined for reactions (6), (8), (9), and (10), which correspond to the oxidation of silicon, carbon to carbon dioxide, and the oxidation of harmful impurities of sulphur and phosphorus. The indicated corresponds to the well-known fact of increased dephosphorization when using coherent nozzles.

Taking into account the limitation of the possibility of electricity consumption, an alloy with a relatively low melting point (compared to the melting point of cast iron and steel of about 1300–1500 °C) was chosen for modelling the oxidation processes of liquid metal impurities. It is important that the aggregate state of the initial components and reaction products should be similar to the aggregate state of hot metal components. Consequently, the thermodynamic parameters of oxidation processes of hot metal impurities and metals in known metal systems were analyzed. It was found that under real conditions, during the oxidation of liquid hot metal with impurities (C, Si, and Mn), the ratio of the Gibbs energies of the oxidation of Si and Fe, for example, correspond to the ratio of the Gibbs energies of the oxidation of Zn and Cu, which, as a brass alloy, have a melting point significantly lower than the melting temperature of hot metal (1000–1100°C depending on the share of zinc versus 1300–1500 °C for hot metal) (**Table 1**).

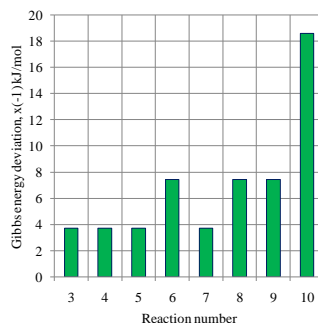


Fig. 2 The values of the deviation of the calculated Gibbs energy for the experimental and comparative nozzles for chemical reactions 3–10

Table 1 The ratio of the Gibbs energies of the oxidation processes of the main components of cast iron and components of the model melt

Oxides, the oxidation processes of which are compared	The ratio of Gibbs energies at liquid state temperatures
SiO ₂ /FeO	2.76
MnO/FeO	2.63
CO/FeO	0.40
ZnO /Cu ₂ O	2.98

In addition, the initial components and reaction products for the oxidation processes of silicon in iron and zinc in brass are similar.

Accordingly, in the conducted modeling, the oxidation process of silicon in the composition of hot metal was studied on the model of the zinc oxidation process in the composition of brass. The zinc content has been adjusted to 1% to ensure comparability. Blowing was carried out in a laboratory setup, which is presented in **Figure 3**. Blowing took place through a coherent nozzle with a share of the peripheral part of 75% compared to blowing through a cylindrical nozzle with an equivalent diameter of $3.2 \cdot 10^{-3}$ m. The total weight of the metal component (brass L96 - zinc content 5% and copper M1 purity 99.99) was 11.4 kg. The blowing time was approximately 1.5 min for all variants. Metal samples were taken before the blowing after the total melting of metal components and during blowing every 20 s (sampling duration was approximately 5 s). The blowing was carried out with technically pure oxygen from a cylinder.

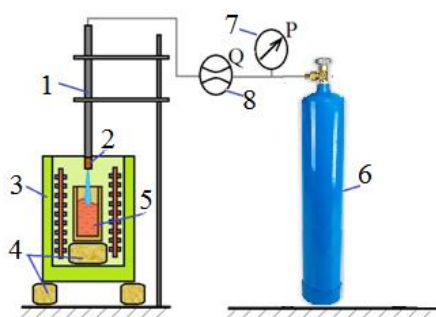


Fig. 3 Functional scheme and image of the experimental setup for studying the effect of a gas jet on the oxidation processes of melt components on liquid metals: 1 – laboratory lance; 2 – the tip of the lance; 3 – resistance furnace with nichrome heaters; 4 – ceramic stands; 5 – fireclay crucible with Cu-Zn system melt (1% Zn); 6 – oxygen cylinder; 7 – manometer; 8 – rotameter.

RESULTS AND DISCUSSION

Three experiments were conducted on oxygen blowing using a coherent-type nozzle and using a comparative nozzle (**Table 2**). First of all the obtained results were averaged and compared

with the available data of iron blowing (with the process of silicon oxidation) in a model of a BOF converter through a single-nozzle lance with a nozzle diameter of $3.5 \cdot 10^{-3}$ m (**Figure 4**).

Table 2 Results of studies of impurity oxidation when using different types of nozzles for top blowing*

Blowing time, s	Zinc content in brass for different nozzle	
	comparative	coherent
0	0.90-0.95 0.92	0.91-0.93 0.92
20	0.22-0.27 0.24	0.19-0.22 0.21
45	0.15-0.19 0.18	0.14-0.16 0.15
70	0.11-0.14 0.12	0.09-0.11 0.10
95	0.09-0.11 0.10	0.07-0.08 0.08

* the numerator shows the run-up range (minimum-maximum value) and the denominator shows the average value for each measurement

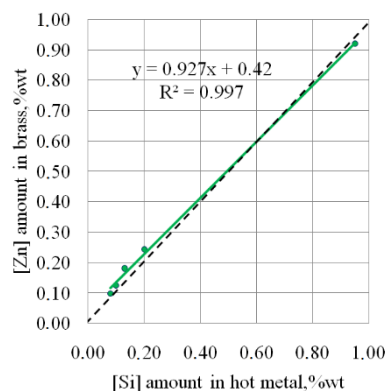


Fig. 4 Comparison of the results of laboratory studies of changes in the content of silicon in hot metal and zinc in brass when blowing through a single-nozzle lance with similar nozzle parameters

It should be noted that the change in the zinc content in the brass during the blowing of the metal bath corresponds to the change in silicon in hot metal during similar periods of blowing. The degree of correlation corresponds to 0.997. The results obtained make it possible to conclude that the modelling using alloys of the Cu-Zn (1%) system can be used to quantify the effect of the design of blowing devices on the efficiency of silicon oxidation processes in a metal bath.

An analysis of the experimental data given in **Table 2** allows concluding that coherent-type nozzles contribute to obtaining a more stable result with a small deviation from the average value in comparison with cylindrical ones. The calculation of the standard deviation of the data for the two nozzle designs was 0.011-0.026 and 0.01-0.015 for the cylindrical and the coherent nozzle, respectively.

Additionally, when using a coherent nozzle, the level of zinc in brass is lower during the total blowing time. The final content of zinc was 17.7% relatively lower. An analysis of the change in the rate of zinc oxidation during blowing when using two types of analyzed design nozzles showed (**Fig. 5**): the greatest advantage of using a coherent nozzle was noted in the initial period up to 20% of the duration; from the middle of the blow, the oxidation rate of the compared nozzle designs is almost the same.

The established feature was probably due to the deeper penetration of the gas jet and intensive mixing in the case of using a coherent nozzle. The oxidation rate decreasing during blowing can occur due to the more difficult oxidation of low (less than 0.2% by weight) zinc contents and the accuracy of its determination at concentrations close to the threshold of determination by the X-ray spectral method.

This indicates the possibility of achieving more intense oxidation and reducing the time to reach low concentrations of impurities in industrial conditions using a coherent-type nozzle by about 10%.

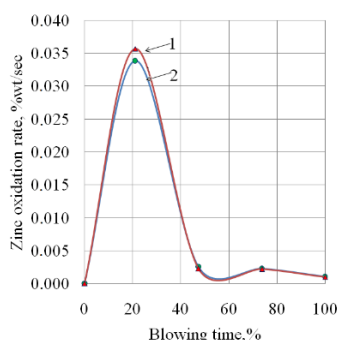


Fig. 5 Changes in the zinc oxidation rate during blowing through a single-nozzle lance with the coherent-type nozzle (1) and comparative nozzle (2)

CONCLUSIONS

The use of coherent-type nozzles in the conditions of BOF oxygen blowing is a rather promising direction of oxidising impurities. The top blowing nozzles of the coherent type, due to their deeper penetration into the melt, should contribute to the activation of oxidation processes of the main impurities of the hot metal (silicon, carbon, and even phosphorus) in comparison with cylindrical nozzles of equivalent diameter.

The conducted high-temperature study of the effect of blowing through the coherent type nozzles on the process of silicon oxidation in a metal bath, based on the use of a liquid Cu-Zn metal alloy (1% Zn), confirmed the conclusions regarding the activation of the oxidation of the main components of the melt. It was established that when using a coherent type nozzle with a peripheral part of 75% for blowing, more intensive oxidation occurs and the duration of the admixture reaching the appropriate low concentrations is reduced by approximately 17.7% compared to blowing through an equivalent cylindrical nozzle of $3.2 \cdot 10^{-3}$ m. Accordingly, when using a proposed type of nozzle in industrial conditions, it is most expected to reduce the blowing time by 10%.

Additionally, the use of metal systems (for example, Cu-Zn (1%)) with a lower melting point than hot metal for high-temperature modelling of oxidation processes of its main impurities, which are chosen under conditions of thermodynamic similarity of oxidation processes and aggregate state of derivatives and reaction products, is a permissible energy-saving modelling method with a sufficient degree of accuracy.

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