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PATTERNS OF DETERMINING METAL LOSSES DURING LANCING OF A CONVERTER BATH WITH IMMERSION OXYGEN-GAS TORCHES

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Abstract. Based on theoretical and experimental studies, the authors consider the features of the formation of metal losses during lancing of a converter bath with immersion oxygen-gas combustion torches using natural gas. The main approaches and the concept of oxygen-fuel converter equipment for the implementation of processes with elements of liquid-phase recovery of various man-made waste were formulated. The causes of possible metal losses are the development of dust release processes associated with the removal of metal and slag droplets, and smoke release processes during evaporation of substances in a high-temperature reaction zone. The main reasons that cause increased metal loss include the crushing of metal into droplets due to the dynamic energy of gas jets followed by the ejection of droplets into the jet, the splashing and spraying of metal by CO bubbles upon reaching the bath surface, and the evaporation of metal in high-temperature reaction zones. The measures allowing to reduce metal losses during the implementation of oxygen-fuel processes in converters were analyzed. The addition of gaseous or liquid fuel to the oxygen stream reduces dust carryover from the evaporation of iron in the reaction zone. This method is quite easy to implement in practice. At the same time, such lancing reduces the influence of other factors that cause additional dust formation. With a decrease in the reaction zone temperature, the manifestations of the smoke emission process decrease.

Keywords: converter, oxygen-gas torch, metal losses, resource- and energy-saving technologies

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ЗАКОНОМЕРНОСТИ ОПРЕДЕЛЕНИЯ ПОТЕРЬ МЕТАЛЛА ПРИ ПРОДУВКЕ КОНВЕРТЕРНОЙ ВАННЫ ПОГРУЖНЫМИ ГАЗОКИСЛОРОДНЫМИ ФАКЕЛАМИ

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Аннотация. На основании теоретических и экспериментальных исследований авторы рассматривают особенности формирования потерь металла при продувке конвертерной ванны погружными газокислородными факелами горения с использованием природного газа. Сформулированы основные подходы и концепция оборудования кислородно-топливных конвертеров для реализации процессов с элементами жидкофазного восстановления различных техногенных отходов. Причинами возможных потерь металла являются развитие процессов пылевыведения, связанных с выносом капель металла и шлака, и процессы дымовыведения при испарении веществ в высокотемпературной реакционной зоне. К основным причинам, которые вызывают повышенный угар металла, можно отнести дробление металла на капли за счет динамической энергии газовых струй с последующей эжекцией капель в струю, разбрызгивание и распыление металла пузырями СО при выходе на поверхность ванны и испарение металла в высокотемпературных реакционных зонах. Проанализированы мероприятия, позволяющие снизить потери металла при реализации кислородно-топливных процессов в конвертерах. Добавка газо-

образного или жидкого топлива к кислородному потоку уменьшает пылевынос от испарения железа в реакционной зоне. Этот способ достаточно легко реализуется на практике. Одновременно при такой продувке снижается влияние и других вызывающих дополнительное образование пыли факторов. При снижении температуры реакционной зоны уменьшаются проявления процесса дымовыделения.

Ключевые слова: конвертер, газокислородный факел, потери металла, ресурсо- и энергосберегающие технологии

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INTRODUCTION

Under current conditions, improving the efficiency of converter processes is closely associated with the development of resource- and energy-saving technologies involving the use, together with scrap as coolants, of various iron-bearing concentrates, complex reducing agents, and all types of man-made waste.

Previous experience [1 – 3] with such processes involving combined lancing and elements of liquid-phase recovery shows that, in the most rational technological variant for semiproduct production, the converter should be equipped with systems for supplying independently controlled oxygen flows with off-gas afterburning, as well as natural gas and inert gas flows to solve various technological tasks. It should also be possible to introduce a significant amount of additional materials and

reducing agents into the melt (see Figure) [4 – 9]. Therefore, obtaining new reliable information on the formation of current metal losses during melting will provide an additional basis for making optimal technological decisions.

ANALYSIS OF METAL LOSSES DURING LANCING OF A CONVERTER BATH

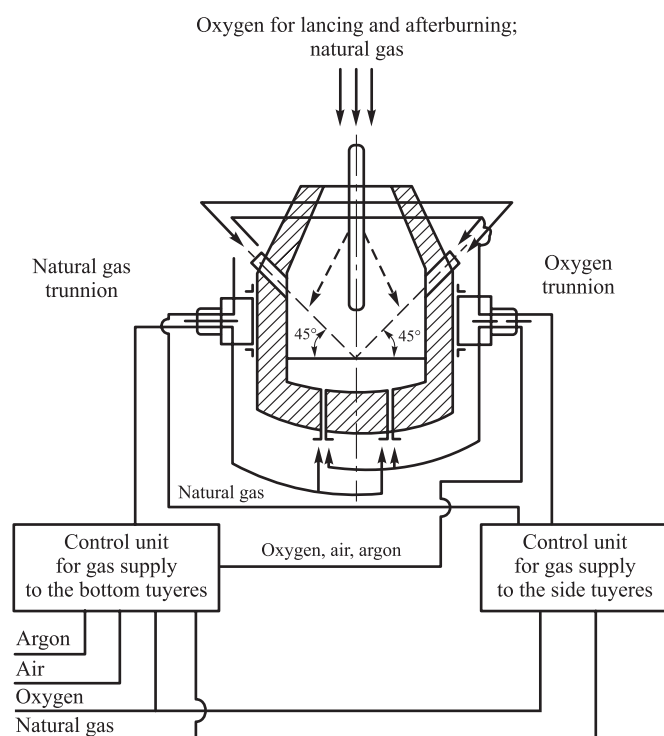
When considering possible metal losses during lancing of a converter bath under the studied conditions, it is necessary to distinguish between dust release associated with the carryover of metal and slag droplets and particles of bulk materials from the converter by off-gases, and smoke release caused by evaporation of substances in high-temperature reaction zones, followed by partial condensation of vapors in the “colder” upper levels of the working space [10; 11]. Intense brown smoke release during lancing is a significant feature and disadvantage of this process. It largely depends on the temperature in the reaction zones and the intensity of bath mixing, with losses reaching 0.8 – 1.5 % of the metal charge mass. Depending on the off-gas flow rate, which is governed by the decarburization rate, and on the degree of foaming of the slag–metal emulsion, the dust content may be 80 – 120 g/m³ and, in some cases, even 250 – 350 g/m³. Iron losses with dust may reach 0.4 – 1.2 % [10 – 12].

Overall, the indicators determined from practical data show rather significant metal losses and a decrease in the yield of liquid steel during bath lancing with immersed jets. Therefore, these losses must always be analyzed and taken into account [12 – 14].

The main reasons for increased metal losses include:

- breakup of metal into droplets due to the dynamic energy of gas jets, followed by entrainment of fine droplets measuring 10^{-3} – 10^{-5} m into the jet;
- splashing and atomization of metal by rising CO bubbles when they reach the bath surface, taking into account the energy of bubble film rupture;
- evaporation of metal in high-temperature reaction zones.

With certain assumptions, the breakup of metal into droplets due to the dynamic energy of the jet can be rep-



Oxygen-fuel converter for steel smelting with elements of liquid-phase recovery of man-made waste

Кислородно-топливный конвертер для выплавки стали с элементами жидкофазного восстановления техногенных отходов

resented as the work required to form a new surface and expressed as follows

$$A = S\sigma, \quad (1)$$

where S is the interfacial surface area, m^2 ; σ is the specific surface tension, erg/m^2 . For example, at $|C| = 1.0 \div 1.5 \%$, for iron–carbon melts, depending on the carbon content, σ may be taken as $1250 \cdot 10^4 \text{ erg}/\text{m}^2$ [15].

According to the data reported by V.I. Baptizmansky and V.B. Okhotskii [10; 16], slightly more than 1.0 % of the dynamic energy of the jet at the nozzle outlet is consumed in forming a new surface, that is, in metal breakup and droplet entrainment into gas jets.

Then, the interfacial surface area is:

$$S = \frac{A}{\sigma} = \frac{0.01E_{O_2}}{\sigma}, \quad (2)$$

where E_{O_2} is the dynamic energy of the jet at the nozzle outlet.

If the jet velocity at the outlet of Laval nozzles is taken to be approximately 350 – 450 m/s, then, at an oxygen flow rate of 1 m^3 , a gas–metal–slag surface of 65 – 70 and even 150 – 350 m^2 may form at a high degree of melt breakup into droplets [12; 16; 17].

The specific surface area of dust particles can be determined from their known size [18]:

$$S_{\text{sp}} = \frac{6}{\rho_a^{\text{Me}} d}, \quad (3)$$

where ρ_a^{Me} is the density of the atomized metal; d is the particle diameter.

Thus, with an average dust particle size of 10 – 25 μm , the specific surface area is 32 – 60 m^2/g , and 1 m^3 of injected oxygen can form 1.10 – 1.82 g/m^3 or more of dust as a result of metal atomization.

As a result of mechanical atomization of metal by gas jets, the gases leaving the reaction zones will contain a significant amount of metallic dust, especially in the initial period of converter bath lancing, when there is no foamed slag layer, and during intense gas evolution at a high carbon oxidation rate. In addition, at the beginning of lancing, when the carbon content is high, the surface tension of the metal decreases, which contributes to an increase in the newly formed surface and, therefore, in the amount of dust carried away [15].

Under these conditions, the velocity of gas jets formed in the nozzles of lancing devices may significantly exceed the speed of sound, which sharply increases the dynamic energy of the gas jets [10]. As a result, the amount of metal atomized by gas jets may reach 5 – 250 g/m^3

of off-gas and, during collapse of the foamed slag layer, even 250 – 350 g/m^3 [10; 19]. This source of dust formation is difficult to control because, in almost all processes involving gas lancing of the converter bath, the outlet velocity of the oxidizing lancing jets is intentionally increased to improve oxygen assimilation and bath mixing.

The only practical technical method for reducing metal atomization by a gas jet is to submerge the jet deeper into the bath. In this case, the dust formed may be reabsorbed by the bath, while a significant part of the jet energy is used to form the metal–slag–gas interfacial surface and to generate additional convective flows and circulation zones. The basic oxygen converter process with bottom lancing is an example of reduced dust release due to submergence of the reaction zone into the bath [20 – 22].

During bath lancing with combustion torches, metal splashing will be much more intense than during oxygen lancing because of the injection of a larger gas volume. A known possible solution for reducing splash formation is additional bath mixing through mechanical rotation of the lancing devices or of the unit itself [10; 23 – 25]. In this case, the volume of the reaction zone increases 3 – 5 times compared with conventional lancing, and the jet energy is consumed not in splashing the melt, but in additional formation of the interfacial surface [25].

It is of interest to assess metal atomization caused by rising carbon monoxide (CO) bubbles, which is determined primarily by their rate of ascent to the bath surface. According to V.I. Yavoisii [12], the bubble rise velocity U can be determined by the following relationship

$$U = U_0 + \frac{m_{O_2}^2 \omega_{O_2}^2}{2mg} + \frac{V_{CO} \rho h}{m}, \quad (4)$$

where U_0 is the convective velocity of the metal caused by the density difference in the melt; this velocity is small and may be neglected; m_{O_2} is the mass of injected oxygen, kg/s; ω_{O_2} is the oxygen outlet velocity from the nozzle, m/s; m is the mass of metal entrained into circulation by the jet, kg; V_{CO} is the CO formation rate, m^3/s ; ρ is the metal density, kg/m^3 ; g is gravitational acceleration, m/s^2 ; h is the bath height at rest, m.

Calculations show that, for various converter process variants, U does not exceed 5 m/s [12; 16]. It follows that the energy developed by CO bubbles during their ascent is hundreds of times lower than the energy of the injected oxygen jet. Therefore, it may be assumed that CO bubbles generate correspondingly less dust when they reach the surface. It should also be noted that, as a bubble rises under the action of drag forces and ferrostatic pressure, it assumes a mushroom-like shape. The rise velocity of a bubble of this shape can be calculated using the empirical equation [26]:

$$U = \frac{R^{0.4} \sigma_{Me}}{k \rho_{Me}^{0.056} \eta_{Me}^{0.5}}, \quad (5)$$

where R is the maximum bubble radius, m; k is an empirical constant; ρ_{Me} , σ_{Me} and η_{Me} are the density, surface tension, and dynamic viscosity of the metal, respectively.

A number of researchers have also indicated intense dust formation during the rupture of rising bubble shells [19; 27]. The main evidence in this case includes the known increase in dust formation intensity with increasing melt decarburization rate and, in general, the dependence of the amount of dust formed on the carbon content in the metal. At the same time, the energy of bubble rupture depends on the partial pressure of the gas inside the bubbles. According to [28], at the initial moment of bubble nucleation, the pressure is approximately 10^7 N/m². As the bubble rises to the bath surface and, accordingly, increases in size, the pressure inside it decreases and is determined by the ambient pressure and the surface tension of the liquid phase. According to [15], the surface tension σ between gas and slag, for example, in the FeO–CaO–SiO₂ system, is in the range of 500 – 600 mJ/m². For metal, the surface tension is much higher, and for a melt with $[C] \approx 1$ %, it may be approximately 1250 mJ/m².

Thus, when CO bubbles reach the bath surface, they are surrounded by a metal film and are conventionally referred to as metal beads. The amount of metal carried away in this form depends on the total surface area of CO bubbles and may reach 8 – 11 % of the slag mass [10; 11]. The metallic dust carried away from the lancing zone may contain up to 60 – 65 % pure iron.

Depending on their size, the particles formed during bubble rupture may either be carried away by off-gases into the gas duct or settle back into the metal bath. The intensity of their return can be determined with sufficient accuracy according to fluidized-bed theory [26]. Other conditions being equal, this intensity is proportional to the difference between the densities of the particle and the off-gas

$$\xi \equiv \sqrt{\rho_{Me} - \rho_{off}}, \quad (6)$$

where ξ is the intensity of droplet return to the melt; ρ_{Me} and ρ_{off} are the densities of the carried-away particle and the off-gas, respectively.

The particle mass depends on whether the particle is oxidized, which, in turn, is determined by the composition of the gas phase above the melt. At sufficiently high temperatures and oxidizing potential of the gas phase, particle oxidation may proceed further, with a significant decrease in particle density and, accordingly, increased carryover.

Therefore, according to relationship (6), oxidation of atomized metal particles should be avoided, since it

subsequently prevents their settling into the metal bath and increases dust carryover. To achieve this goal, efforts should be made to reduce the oxidizing potential of the gas phase in which bubbles rupture when they reach the surface. This approach can be implemented, for example, by diluting the top-lancing jet with various fuels or inert gas [29 – 31]. Previously obtained data on oxygen lancing of metal with nitrogen dilution [29] show that this method reduces dust release in proportion to the amount of nitrogen introduced to dilute the gas flow. However, such lancing methods have not become widespread because they reduce the rates of oxidation reactions and bath heating. Considering the available data, a more acceptable lancing method is the addition of fuel to oxygen, which, along with reducing dust release, introduces an additional amount of heat into the bath [3]. Calculations of equilibrium conditions between the metal and a gas phase consisting of a stoichiometric mixture of oxygen and methane show that the gases leaving the reaction zone contain a significant amount of CO and H₂. In their presence, formation of iron oxides is unlikely or impossible [30]. Therefore, it is obvious that, under these conditions, dispersed metal particles will settle into the bath to a greater extent and will be carried away with off-gases to a lesser extent.

The addition of fuel to oxygen decreases the decarburization rate, which also helps reduce the amount of dust formed during rupture of gas bubbles and breakup of films of metallic beads.

According to current concepts [10], evaporation of the iron and manganese oxides formed in the reaction zone has a significant effect on the temperature of this zone. Heat consumption associated with evaporation limits and slows down a considerable increase in the reaction-zone temperature, while the limiting temperature values are obviously determined by the boiling conditions of iron at 2735 °C. Numerous experimental studies have established that, during lancing of the melt with technically pure oxygen, the temperature in the interaction zone is approximately 2100 – 2700 °C, while overheating relative to the volume of the lanced bath is 700 – 900 °C. This overheating depends on the carbon content in the metal, the decarburization rate, and the lancing intensity and therefore changes during converter melting [16; 32].

When accounting for iron evaporation in the reaction zone, it should also be considered that, with increasing temperature, the vapor pressure of iron increases exponentially according to the equation:

$$\lg P_{Fe} = \frac{18,500}{T} + 8.025, \quad (7)$$

where P_{Fe} is the vapor pressure of iron, mm Hg.

Calculations performed by analogy with studies [10; 15] show that, at this degree of overheating in

the reaction zone, the vapor pressure of iron does not exceed 0.04 atm, or 30.4 mm Hg, resulting in the formation of 4 – 8 g/m³ of dust. Thus, evaporation leads to significant additional dust carryover.

At the same time, it can be stated that, in terms of significance, this source of dust formation is close to losses caused by the dynamic action of the jet and losses caused by rupturing gas bubbles. Therefore, it is not dominant, as is often assumed. This also explains why attempts to eliminate smoke formation by injecting various coolants into the reaction zone, although they significantly reduce it, do not solve the problem fundamentally. It is therefore obvious that evaporation in the reaction zone does not play a determining role in dust formation during lancing of a converter bath.

This is confirmed by the well-known decrease in the amount of dust in the off-gases of oxygen converters at the final stage of lancing, that is, at the end of melting, despite the bath temperature being much higher during this period than at the beginning of the process. At the same time, it should be noted that evaporation does play a certain role in dust formation. Therefore, various options for cooling the reaction zone reduce smoke release and dust carryover during steelmaking.

Thus, the addition of gaseous or liquid fuel to the oxygen lancing jet is a reliable and sufficiently easy-to-implement method for reducing dust carryover caused by iron evaporation in the reaction zone [3]. This lancing variant will simultaneously reduce the effect of many other factors that cause additional dust formation. In addition, introducing gaseous or liquid fuel into the converter together with oxygen through high-power lance burners additionally increases the heat input into the bath.

CONCLUSIONS

Theoretical and experimental studies have established that fuel addition to oxygen jets and the implementation of oxygen-gas lancing are effective methods for reducing dust formation during converter melting. This technical solution reduces the temperature of the reaction zone and, accordingly, smoke release; changes the oxidation behavior of atomized metal droplets; and promotes particle coagulation and their return to the metal bath.

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