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Environmental features of oxidative refining of phosphorous hot metal in heavy-duty converters

I. K. Ibraev, **O. T. Ibraeva**

Karaganda State Industrial University (30 Respubliki Ave., Temirtau, Karaganda Region 101400, Republic of Kazakhstan)

ibraevik@yandex.ru

Abstract. The article discusses a new method for estimating the amount of dust emitted from the converter bath during oxygen blowing of phosphorous hot metal. This method allows one to determine how technological solutions and blast modes affect the environmental performance of the production process. The study identified the causes of increased dust emission and developed the solutions to improve the environmental performance of the plant. Dust and gas emissions from the converter shop fall into two categories: organized and disorganized. Organized emissions are captured at the outlet of the converter mouth, and disorganized emissions occur periodically during cast iron casting, scrap loading, metal and slag discharge. These emissions contain dust, heat, carbon monoxide, nitrogen and sulfur oxides, and aluminum fluorides. Resource-saving technology using inactive slag reduces emitting of dust and gases by using active foamed slag at the initial stage of blowing and reducing lime consumption. Matching the gas volume to the exhaust duct's through-put reduces dust removal by 30 – 40 % and unorganized emissions by 83 %. Reduction of carbon monoxide emissions is achieved by increasing the rate of rise in the CO concentration to the ignition limits, followed by afterburning on the "flare" and organizing melting with a shortened first heating period. Reducing the phosphorus content of cast iron to 0.3 wt. % decreases lime consumption from 143 to 77 kg/t of steel, the duration of blowing and heats by 10 – 16 %, lime production and increases the productivity of converters. A comprehensive approach to reducing dust and gas emissions includes optimizing processes, introducing new materials and technologies, and monitoring and analyzing performance indicators. This improves the environmental situation and increases production efficiency.

Keywords: dust and gas emissions, emission, gas exhaust duct, blowing, hot metal, converter smelting, phosphorous conversion, lime, metal, slag

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Экологические особенности окислительного рафинирования фосфористых чугунов в большегрузных конвертерах

И. К. Ибраев, **О. Т. Ибраева**

НАО «Карагандинский индустриальный университет» (Казахстан, 101400, Карагандинская обл., Темиртау, пр. Республики, 30)

ibraevik@yandex.ru

Аннотация. В статье рассматривается новый метод оценки количества пыли, выделяемой из конвертерной ванны при продувке кислородом фосфористых чугунов. Этот метод позволяет определить, как технологические решения и режимы дутья влияют на экологические показатели процесса. В ходе исследования были выявлены причины повышенного выделения пыли и разработаны решения для улучшения экологических характеристик. Выбросы пыли и газов в конвертерном цехе делятся на две категории: организованные и неорганизованные. Организованные выбросы улавливаются при выходе из горловины конвертера, а неорганизованные происходят периодически во время заливки чугуна, загрузки лома, слива металла и шлака. Эти выбросы содержат пыль, тепло, угарный газ, оксиды азота и серы, а также фториды. Ресурсосберегающая технология с использованием неактивного шлака снижает выделение пыли и газов за счет использования активного вспененного шлака на начальной стадии продувки и уменьшения расхода извести. Соответствие объема газов пропускной способности тракта снижает вынос пыли на 30 – 40 % и неорганизованные выбросы на 83 %. Снижение выбросов угарного газа достигается за счет увеличения скорости нарастания концентрации CO до пределов воспламенения с последующим дожиганием на «свече» и организации плавки с укороченным первым периодом. Снижение содержания фосфора в чугуне до 0,3 мас. % уменьшает расход извести с 143 до 77 кг/т стали и продолжительность продувки и плавки на 10 – 16 %, сокращает производство извести и повышает производительность конвертеров. Комплексный подход к снижению выбросов пыли и газов включает оптимизацию процессов, внедрение новых материалов и технологий, мониторинг и анализ показателей. Это улучшает экологическую ситуацию и повышает эффективность производства.

Ключевые слова: пыле-газовыделение, выброс, газоотводящий тракт, продувка, чугун, конвертерная плавка, фосфористый передел, известь, металл, шлак

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Introduction

With the development of the digital economy and the depletion of natural resources, the issue of resource efficiency is becoming increasingly relevant. Resource efficiency is considered in terms of environmental safety, environmental protection, and the development of renewable energy sources. Measures are being taken to reduce emissions, discharges, waste generation, and to improve waste utilization.

Global steel production has exceeded 1.9 billion tons, with more than 70 % produced in converters. For every ton of steel, 15 – 25 kg of dust is generated, requiring energy for gas cleaning and leading to energy and resource losses.

Abroad, cost-effective and high-performance processes are being developed for processing low-phosphorous hot metal with heat durations of up to 40 min in converters with capacities of 250 – 400 t. These technologies ensure high yield of marketable steel and low consumption of refractories and basic materials.

At Qarmet JSC, the specific dust emission ranges from 25.5 to 31.36 kg/t [1; 2], due to the use of low-grade iron ore, the lack of natural gas, high ash content of coal, and the deterioration of metallurgical units. The use of phosphorous feedstock increases material and energy consumption due to its low metallurgical value and the high ash content of coal.

Processing hot metal with a phosphorus content above 1.0 wt. % from low-grade iron feedstock adversely affects the technical and economic performance of the blast furnace shop. The specific productivity of blast furnaces at Qarmet JSC is 30 – 35 % lower, and specific coke consumption is 25 – 30 % higher than at other enterprises. Resource consumption per ton of hot metal and steel increases, leading to a 20 – 25 % rise in metal production costs [3].

Converter processing of high-phosphorous hot metal at Qarmet JSC requires a two-slag process, which increases the duration of the heat by 7 – 12 min and reduces the service life of the lining due to the aggressiveness of the highly oxidized slag. Lime consumption reaches 120 kg/t, and slag output increases to 270 kg, leading to additional iron losses in the slag [3; 4].

Reducing dust and gas emissions from the converter bath requires a comprehensive approach, including process optimization, the introduction of new materials and technologies, and continuous monitoring and analysis. These measures improve environmental conditions and enhance production efficiency.

Literature review

In non-CIS countries, the environmental situation in the ferrous metallurgy sector is comparable to that in Russia and other CIS states. For example, emissions from ferrous metallurgy enterprises account for about 15 % in the United States and 15 – 18 % in the CIS countries [5 – 8]. A noteworthy example is Germany, where the implementation of advanced technologies has significantly reduced dust emissions from 3 to 1 kg/t of steel and completely eliminated the generation of contaminated wastewater. Captured dust is returned to the process, and purified converter gas is used as a fuel, providing 0.72 GJ of heat per ton of steel [8; 9]. In Russia, this figure ranges from 4.5 to 11.0 kg/t.

When processing open-hearth hot metal in top-blown converters (LD process) with prepared scrap, dust emissions amount to 7 – 10 kg/t, and specific carbon monoxide emissions reach 14 – 16 m^3 per ton of produced steel. With combined blowing (oxygen injection from both top and bottom), dust emissions are significantly reduced. According to data from the Tibe Plant (Japan), dust emissions during combined blowing range from 2.5 to 4.0 kg/t. This reduction is attributed to reduced iron oxidation losses and decreased lime consumption [10; 11].

When analyzing potential metal losses during converter bath blowing, it is important to distinguish between dust emissions, which are associated with the removal of metal droplets, slag, and bulk material particles by the off-gas stream, and gas emissions, which result from the evaporation of substances in high-temperature reaction zones followed by partial condensation in the cooler upper areas of the converter volume [12].

Intensive formation of brown fumes during blowing is a major drawback of the process and largely depends on the temperature in the reaction zones, the bath mixing intensity, the blowing mode and nature of additions, the design and positioning of the lance, the blowing intensity, and the maximum rate of decarburization [12; 13]. Depending on the gas flow rate (decarburization rate) and the degree of foaming of the slag-metal emulsion, dust concentrations can reach 80 – 120 and even 250 – 350 g/m^3, while iron losses in the dust can be as high as 0.4 – 1.2 % of the metal charge.

Typically, metal losses due to fume during oxygen blowing amount to 0.8 – 1.5 % [14]. In general, practical data indicate that blowing with submerged jets causes significant metal losses and reduces the yield of liquid steel. These losses require additional analysis and consideration.

Dust particle size depends on the process temperature and cooling rate. At the start of blowing, when the bath is still cold (below 1300 °C), the dust consists mainly of coarse particles (average size around 5 μm). When the bath temperature reaches 1600 – 1700 °C, a large proportion of particles fall within the 0.02 – 0.10 μm range [14; 15].

The method of charging bulk materials significantly affects dust concentration and the particle size distribution of the resulting dust. On average, dust collected during melting contains (by weight) 60 – 70 % metallic iron, 5 – 17 % lime, and 0.7 – 3.0 % silicon [16; 17].

The degree of dust formation also depends on the design of the oxygen lance, including the angle of the nozzles relative to vertical. Increasing the nozzle inclination angle causes the jet to spread over a larger surface area, which improves slag formation conditions. When the angle is increased from 8 to 20° and the oxygen flow rate through each nozzle is 75 m^3/min, fine dust emission decreases by 30 %. The use of oxygen lances equipped with four or five nozzles angled at 15 – 20° enables greater dispersion of the reaction zone, reducing dust emission from 17.7 to 10.8 kg/t. In this case, the rate of increase in dust formation lags behind the increase in blowing intensity [17; 18].

One promising direction for improving both the technical-economic and environmental performance of the converter process is the implementation of a gas-jet shielding system, which is created by supplying elastic jets of oxygen or other gases to form a gas curtain above the blowing zone [18 – 20]. This approach reduces the carryover of process dust, metal splashes, and slag from the converter, significantly improving the technical and quality characteristics of the produced steel, enhancing thermal and environmental process parameters, and reducing the costs of off-gas dust removal systems.

The high phosphorus content of hot metal necessitates the use of special technological solutions to minimize emissions, which is essential for improving working conditions and protecting the environment. This literature review highlights the need for continuous improvement of technologies and the implementation of innovative solutions aimed at reducing the negative environmental impact of steelmaking.

Research methodology

Since it was not feasible to directly collect dust samples from the high-temperature dust-and-gas flow exiting the converter bath due to the elevated temperature (above 1200 °C), high measurement error, and the risk of carbon monoxide poisoning, a safe method was developed to estimate dust removal from the converter bath based on the concentration of suspended solids in the slurry water (*i.e., sludge-contaminated water from gas cleaning*) at the final stage of converter gas treatment (in the solivor) [21].

During the study, samples of suspended solids were collected during control heats. The experimental heats were conducted under different technological conditions:

– with combined blowing;

– with the use of powdered lime;

– with partial slag retention on lump lime;

– with slag retention and shortened first period;

– comparative heats with lump lime and without slag retention.

The average concentration of suspended solids in the slurry water for the entire duration of the heat was calculated using the formula

$$z_{ss} = \frac{FZ^1}{\tau},$$

where F is the area under the curve representing the concentration of suspended solids versus blowing time, mm^2 on the diagram scale $F = 5000$ mg/(L·min); $Z^1 = 5000$ mg/(L·min) is the scale coefficient; τ is the current heat duration, min.

The amount of captured sludge was calculated using the formula

$$G_{sl} = LZ_{ss} \cdot 10^{-9},$$

where L is the water consumption for gas cleaning, m^3/h.

Disorganized dust emissions under excess pressure exceeding 1.5 mm H_2O beneath the skirt were determined by measuring gas. and dust concentration in the roof (monitor) openings of the main building. The number of “smoking” openings was also taken into account.

Gas velocity was measured using a cup anemometer, while dust concentration was determined by external filtration using AFA filters. Gas pressure, temperature, and humidity were measured in accordance with GOST 17.2.4.07–90 and GOST 17.2.4.08–90.

Dust emissions were calculated using the formula

$$A = ZWF\tau,$$

where Z is the dust concentration in the monitor opening of the main building, mg/m^3; W is the gas velocity in the monitor opening, m/s; F is the area of the “smoking” openings, m^2, calculated as $F = fn$, where f is the area of a single opening, and n is the number of “smoking” openings; τ is the duration of the disorganized emission, min.

Results and discussion

Environmental assessment of converter steelmaking technology at Qarmet JSC

In the framework of the study, an analysis was conducted of emissions generated during steel production in the converter shop. The share of emissions relative to total emissions in the industry is 1.45 % for dust, 6 % for carbon monoxide (CO), 0.45 % for sulfur dioxide (SO_2), and 0.5 % for nitrogen oxides (NO_x).

The specific converter gas output is 70 – 90 m^3 per ton of steel, and the specific dust emission ranges from 21 to 32 kg/t for heats cooled with scrap. The average dust concentration in converter gas is 150 – 350 g/m^3, reaching up to 1500 g/m^3 during additions.

The chemical composition of dust emitted from the converter bath is shown in Table 1.

Sulfur enters the converter gas in the form of SO_2, and its amount depends on the sulfur content in the metal charge and slag-forming materials. Up to 14 % of the sulfur contained in the charge is carried away with the converter gases, of which about 1 % transitions into the gas phase, while the rest is adsorbed by converter dust.

Nitrogen oxides are practically not formed in the converter itself; they appear when afterburning of converter gas is performed in the waste heat boiler, where their concentration reaches approximately 100 mg/m^3 (specific NO_x emission – 50 g/t of steel). Without afterburning, NO_x is formed during flare combustion of converter gas, reaching up to 30 g/t of steel. A significant portion of emissions consists of disorganized emissions, which are short in duration but intense.

Dust generation per ton of steel by unit operation is as follows: in the stockyard: 0.03 – 0.09 kg/t, in the bulk material feeding section: 0.04 – 0.06 kg/t, in the mixer section: 0.42 – 0.88 kg/t, in the ladle drying and repair section: 0.01 – 0.02 kg/t, in the ferroalloy preparation section: 0.003 kg/t, in the casting section: 0.10 – 0.12 kg/t. Disorganized emissions are characterized by a wide range of chemical and particle size compositions.

During hot metal tapping, graphite dust is released with flake sizes of 50 – 100 μm, and iron-containing particles range from 1 – 80 μm. When oily scrap is charged into the converter, polycyclic hydrocarbons are released, and in the presence of zinc and lead, vapors of these metals and their oxides are formed. The concentration of organic compounds in the gas during the use of oily scrap reaches 60 mg/m^3, or 5 – 6 kg per ton of charge.

Emissions during tapping are associated with the decarburization of hot metal due to air suction into the bath by the stream of tapped metal. During steel tapping, fine dust is emitted, and during handling of bulk materials, coarse dust with particle sizes of 5 – 200 μm and larger is generated. Dust concentration near the handling points ranges from 1 to 100 mg/m^3. The specific dust emission during hot metal tapping ranges from 0.07 to 0.9 kg/t of hot metal with an average of 0.16 kg/t.

During steel tapping, specific dust emissions range from 0.02 to 0.34 kg/t, averaging 0.09 kg/t of steel. The dust consists of 70 – 75 % iron oxides. When additives are charged into the ladle, dust emissions increase to 3 – 5 g/m^3, with average dust concentration reaching 0.5 – 1.5 g/m^3. The gas emitted from the converter mouth contains approximately $(5 – 10)\cdot 10^{-3}$ wt. % sulfur oxide and a small amount of nitrogen oxide (up to 0.03 g/m^3); the moisture content during pure oxygen blowing is 3 – 5 g/m^3, and dust concentration is 150 – 350 g/m^3. Gas cooling and dust removal occur in the off-gas duct, which consists of a waste heat boiler, gas cleaning unit, blower, and flare.

The operation of the off-gas system without CO afterburning can be divided into three stages. In the first minutes of blowing, air is drawn through the gap between the duct and the converter, enabling complete combustion of CO. The combustion products and air nitrogen create a "buffer" between the extracted air and CO, ensuring explosion safety. After the gap is closed with a movable hood, the process continues without afterburning. At the end of the heat, the hood is lifted and CO is once again burned inside the converter vessel. The amount of generated fume dust depends on the design of the lance, the particle size distribution and quality of fluxing agents, and the temperature of the bath. Dust generation is mitigated by cooling the reaction zone and foaming the slag.

Carbon monoxide (CO) emissions during gas treatment without afterburning occur because, at the beginning and end of the blow, the CO concentration in converter gas is below the level required for combustion.

Table 1. **Chemical composition of dust emitted from the converter bath**

Таблица 1. **Химический состав пыли, выделяющейся из конвертерной ванны**

Blowing period, min	CO/CO_2 ratio	Component content, wt. %							
		Fe	FeO	Fe_2O_3	SiO_2	CaO	MnO	C	S
0 – 4	3.3	2.3	70.2	11.4	4.3	1.5	3.6	1.7	0.19
8 – 14	12.1	26.1	42.3	6.5	3.2	6.3	8.4	1.2	0.18
16 – 20	7.3	29.3	38.7	6.3	3.8	3.7	9.2	0.8	0.12

Disorganized emissions are characterized by a wide range of chemical compositions and particle size distributions. There are two main approaches to addressing environmental pollution caused by disorganized emissions: implementation of gas capture and cleaning systems and improvement of operational technologies, particularly through the use of dust suppression techniques.

The majority of gases generated in converter steelmaking pass through a gas cleaning system, where dust is removed with an efficiency of approximately 89 – 95 %.

Study of dust and gas emissions during oxidative refining of phosphorous hot metal

The gas evolution process during the blowing period is characterized by a steady emission phase in the middle of the heat, preceded by increasing intensity at the beginning and followed by a sharp decline at the end of the heat. The addition of fluxing agents causes bursts of gas evolution.

Measurement results showed that one heat discharges 0.173 t of dust through the flare, which corresponds to 0.57 kg per ton of produced steel. During blowing, 0.53 kg of dust and 8.32 kg of carbon monoxide are emitted per ton of steel. Dust loading measurements of the off-gases at the flare indicated significant variation in dust content throughout the blowing period. To assess the impact of process parameters, samples of slurry water from the gas cleaning system were collected.

The analysis revealed a correlation between dust emissions at the flare and the content of suspended solids in the slurry water from the final stage of gas cleaning (the so-called solivor). This made it possible to establish a closer link between process parameters and the formation and release of dust (Fig. 1).

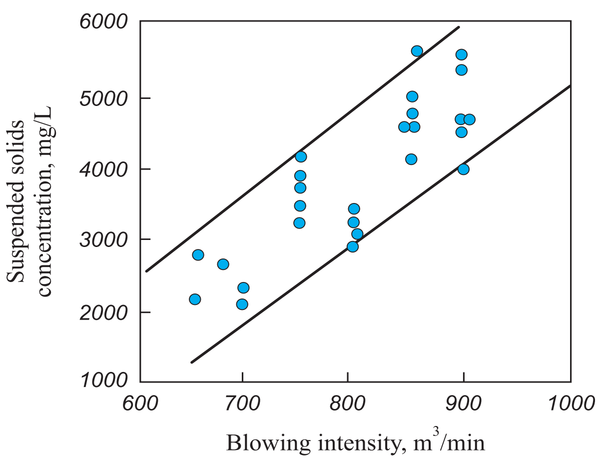

Fig. 1. Effect of blowing intensity on the content of suspended particles in the solivor slurry water in the first period

Рис. 1. Влияние интенсивности продувки на содержание взвешенных частиц в шламовой воде соливора в первом периоде

A qualitative assessment of the data allows for a reliable evaluation of how different process parameters influence dust generation in the converter zone and, consequently, its release into the atmosphere. According to literature data and gas analysis results, the initial blowing period is associated with increasing gas evolution, which is accompanied by a corresponding rise in dust emissions.

In heats with partial or complete slag retention, as indicated by the lower content of suspended solids in the water, dust formation is reduced and increases more gradually and consistently, without sharp peaks that could impair gas cleaning efficiency (Fig. 2).

During the established period of intensive decarburization, all heat variants showed a correlation between the concentration of suspended solids in solivor water and the blowing intensity. However, this dependence was observed only in the interval between additions of bulk materials.

The dust formation process directly depends on the mode of adding bulk slag-forming materials. During the period of intensive decarburization, each addition of bulk slag formers results in a marked increase in gas evolution, causing peak dust emissions from the converter. This is clearly seen in the suspended solids content in the water, as shown in Fig. 3. Such peak emissions degrade the performance of the gas cleaning system and result in disorganized emissions.

Retaining the final slag in the converter promotes the rapid formation of a free-flowing foaming slag after hot metal is tapped and blowing begins. This slag acts as a filter, capturing dust and binding it with calcium oxides in the slag melt. The physical heat of the final slag contributes to a more intensive start of the refining process.

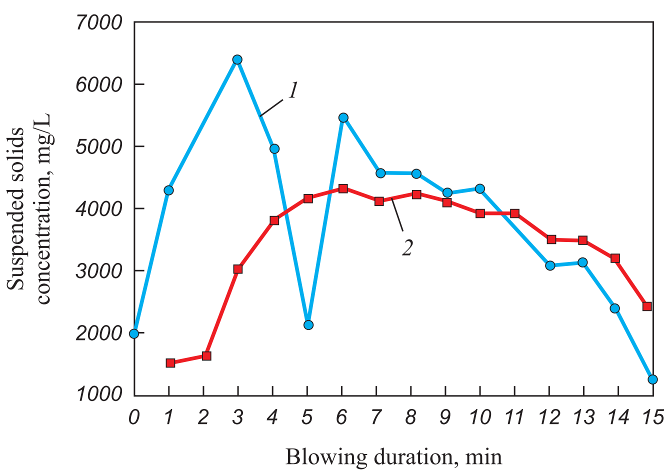

Fig. 2. Change in the content of suspended particles in the solivor water at blowing beginning in heats without (*1*) and with the final slag (*2*)

Рис. 2. Изменение содержания взвешенных частиц в воде соливора в начале продувки на плавках без оставления (*1*) и с оставлением конечного шлака (*2*)

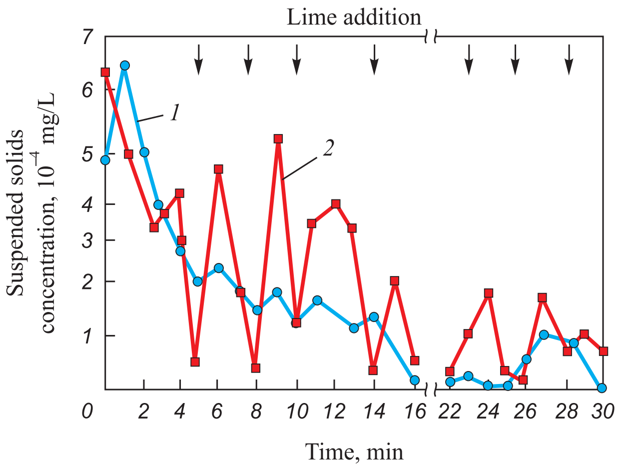

Fig. 3. Effect of lime addition mode on the content of suspended particles in the solivor water

Рис. 3. Влияние режима присадки извести на содержание взвешенных частиц в воде соливора

The presence of ferrous oxide in the slag melt reduces iron oxidation and its loss into the gas-cleaning system.

Peak dust emissions during the developed decarburization stage and lime addition are associated with a sharp increase in the volume of off-gases due to the increased formation of CO and CO_2. This is caused by both the decomposition of carbonates in underburned lime and the accelerated reaction between carbon and oxygen on pre-formed nuclei – specifically, the rough surfaces of the lime particles added.

The increase in gas volume in the converter raises the gas outflow velocity, which disrupts the conditions for lime particle retention inside the converter. Calculations show that when the gas velocity reaches 35 – 40 m/s, lime particles smaller than 8 – 10 mm begin to be carried out of the converter.

Analysis of gas evolution during lime addition to the bath, as described by the system of equations (1) and (2), allows for determination of the parameters needed to control dust and gas emissions from the converter bath:

$$V_{cg} = K_1 \sum O_{2g} + K_2 \sum O_{2k} + V_{uburn} + V_g + V_{H_2O} + V_{H_2}, \quad (1)$$

where V_{cg} is the volume of converter gases, m^3; O_{2g} is the total oxygen flow through the lance; O_{2k} is oxygen consumption delivered with oxygen-containing additives; K_1 and K_2 are the specific gas evolution per 1 m^3 of oxygen from blowing and additives, respectively; V_g is the volume of gaseous combustion products; V_{H_2O} and V_{H_2} are the volumes of water vapor and hydrogen; V_{uburn} are the volumes of CO and CO_2 from the decomposition of underburned lime;

$$V_{uburn} = 0.224 \frac{AG_{lime}}{100\tau} \text{ or } \frac{22.4nG_{lime}}{44 \cdot 100\tau}, \text{ m}^3/\text{min}, \quad (2)$$

where G_{lime} is the mass of the lime batch, kg; A is the percentage of underburned lime, %; n are the calcination losses, %; τ is the current heat time, min.

Based on the obtained data, a new mode of adding bulk materials was developed. Its key principle is to maintain the off-gas volume below the capacity of the converter gas exhaust duct and the induced draft fan.

Research shows that reducing the blowing intensity to 0.5 – 0.7 of its nominal value during bulk material addition helps lower the off-gas volume. To maintain high process performance, the blowing intensity must be restored to its original level after the additions are complete.

It was established that the decarburization process and the associated CO emission do not immediately decrease following a reduction in blowing intensity due to process inertia, but rather after a certain delay. It is recommended to introduce bulk materials after a short holding period, and to restore the original blowing intensity also after a brief delay.

The time interval between the reduction in blowing intensity and the addition of bulk materials, as well as the subsequent increase in intensity, depends on the CO content in the off-gas, as determined by gas analysis. The best results are achieved when the following condition is met: the ratio of the lead time for intensity reduction before addition to the lag time for increasing intensity after addition should be (0.8 – 1.0):(0.3 – 0.1) relative to the CO content in the off-gas, expressed as a percentage.

The developed blowing mode completely eliminates gas ejection from under the converter's "skirt" and reduces dust carryover into the off-gas duct and gas-cleaning system by a factor of 2.5 – 3.3.

When operating the converter under a non-postcombustion system with phosphorous hot metal, CO emissions are observed in the second stage of the heat due to low CO concentrations (below the flammability limit of wet gas mixtures, <35 vol. %) and elevated CO emissions in the initial moments of blowing. This is attributed to the slow rise of CO concentration to flammability levels, resulting in forced CO release into the atmosphere in an amount of 9.3 m^3 per ton of steel, as well as the low decarburization rate and CO evolution during the second stage of the heat.

The high specific CO emissions are attributed to the use of wet gas-cleaning systems for converter gases and the two-slag blowing process. Elevated humidity levels in the converter gas prevent the organization of afterburning on the flare during the initial blowing stage, until the CO concentration reaches the flammability limit.

To increase CO yield, a gas-dynamic method for CO accumulation in the off-gas duct has been proposed. Air dilution of the off-gases under the converter skirt is reduced by lowering the induced draft fan capacity and increasing the oxygen flow rate during the initial stage of blowing. This is followed by a decrease in oxygen flow rate and an increase in fan capacity during the onset of gas outflow and intensive decarburization. This approach reduces CO emissions to 7.6 m^3 per ton of steel.

Interruptions in blowing and converter tilting for intermediate slag tapping prevent effective CO afterburning. However, organizing heats with a shortened first period and a carbon content at turndown of 0.8 – 1.0 wt. % enables CO afterburning before release into the atmosphere, reducing emissions from 21.1 to 15.6 m^3/t of steel. The elevated carbon content allows the second period of the heat to proceed at higher temperatures, reducing thermal losses and increasing the tapping temperature.

A series of experiments, in which the oxygen blowing rate was increased to 1000 – 1100 nm^3/min and the induced draft fan capacity was reduced to 110,000 m^3/h, demonstrated that the time required to reach the CO flammability limit could be shortened. As a result, CO emissions decreased by 7.6 m^3/t of steel.

Heats performed with a shortened first blowing period and a turndown carbon content of 0.9 – 1.0 wt. % resulted in a higher decarburization rate and raised the CO concentration in the off-gases during the second blowing period to 35 vol. % or more. This enabled afterburning of CO on the converter flare.

The implementation of this technology not only reduced atmospheric CO emissions but also decreased heat losses during intermediate turndown, ensured more complete utilization of the chemical potential of hot metal during the second period of the heat, and enabled deeper dephosphorization and desulfurization while reducing total oxygen consumption to an average of 1870 m^3 per heat.

Analysis of disorganized emissions from under the movable converter skirt and through the main shop building's vent lantern indicates that the volume of contaminated gases released from the converter exceeds the capacity of the gas exhaust duct and gas-cleaning equipment. This is primarily due to increased steel production demands, which are being met by increasing converter charge weights and oxygen-blowing rates without upgrading the gas exhaust duct.

Operating converters with increased charge weight not only worsens environmental performance but also reveals a number of drawbacks that reduce the safety of both equipment operation and the steelmaking process. For example, higher converter charge weights result in increased thermal loads on the boiler.

To match the off-gas volume with the throughput capacity of the duct, a converting technology was implemented that uses a reduced converter charge (300 – 320 t versus 360 – 365 t) in combination with decreased blowing intensity (600 – 800 m^3/min versus 800 – 950 m^3/min) of the converter bath with oxygen.

Lower blowing intensity through a four-nozzle lance significantly reduced dust formation by 30 – 40 % (Fig. 4), which also decreased sludge output from the gas-cleaning systems (Table 2). Aligning the off-gas volume from the converter bath with the capacity of the gas exhaust duct by lowering blowing intensity and reducing the converter charge weight reduced disorganized emissions from under the converter skirt from 136 to 22.7 kg per ton of steel, i.e., by 83.4 %.

To ensure the required slag formation and blowing conditions while improving environmental performance, the converter operation was switched to a four-nozzle oxygen lance and a new dynamic blowing mode. Test heats carried out using a single-slag process (for phosphorus content below 0.4 wt. %) and a two-slag process (for phosphorus content above 0.4 wt. %) demonstrated that reducing the converter charge from 365 to 320 t decreased dust emissions from the converter by 15 – 25 %, regardless of lance design.

In addition to improving environmental indicators, the process also enhances the technological and technical–economic performance of converter heats:

– a 1.7 – 2.0 % reduction in slag oxidation;

– a 3.4 – 6.6 % decrease in the share of heats with off-gas emissions, and a 7 – 8 % reduction in the number of heats requiring post-blowing;

– a 2.5 – 3.9 kg/t decrease in hot metal consumption;

– a 0.5 % increase in prime yield.

Blowing at reduced intensity ensures rapid initiation of the heat and an early onset of the decarburization process.

The amount of disorganized emissions is also influenced by the structural elements of the movable skirt when in the raised position. To reduce disorganized emissions and ensure complete capture of off-gases while the movable skirt is in the raised position – during hot metal charging, scrap loading, and the initial blowing phase before the heat ignites and the skirt is lowered to its

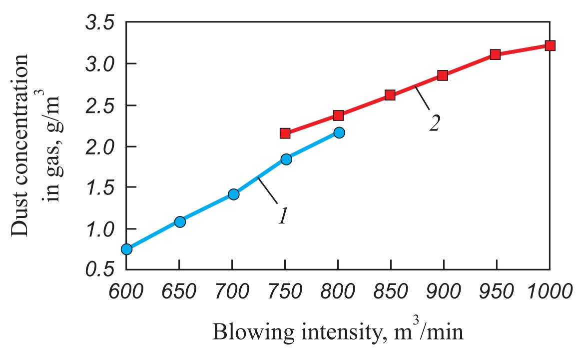

Fig. 4. Effect of blowing mode on dust emitting process:
1 – four-nozzle lance; *2* – five-nozzle lance

Рис. 4. Влияние дутьевого режима продувки на процесс пылевыделения:
1 – четырехсопловая фурма; *2* – пятисопловая фурма

Table 2. **Effect of reduced blowing intensity and converter load on dust removal from the bath**

Таблица 2. **Влияние пониженной интенсивности продувки и садки конвертера на пылевынос из ванны**

Indicators	Fournozzle lance		Fivenozzle lance	
	320 t	361 t	320 t	365 t
Average dust concentration in converter gas before flare, g/m^3	1.8	2.2	2.8	3.2
Specific dust emissions, kg/t of steel	1.43	1.56	2.23	2.31
Specific sludge output after gas cleaning, kg/t of steel	12.5	13.0	18.5	21.8

lowest position – a new skirt sealing design was developed and implemented [22].

To improve the seal reliability between the converter hood and the skirt in its raised position, enhance the durability of the steel structures around the converter mouth, and prevent gas escape, a vertically oriented, water-cooled cylindrical device with a horizontal overhang at its top was installed coaxially with the converter axis. The outer edge of the overhang is flanged and faces downward. A cylindrical sealing shutter is mounted on the horizontal section of the movable skirt, directly opposite the overhang flange. When the skirt is raised, the overhang flange fits tightly into the skirt's sand seal, effectively preventing off-gas leakage and ensuring complete gas capture.

The implementation of this device helped reduce disorganized dust emissions through the main shop vent lantern by 300 t per year.

Effect of phosphorus content in processed hot metal on the environmental performance of oxidative refining

A key solution to improving the environmental safety of metallurgical production – including converter steelmaking – while enhancing the competitiveness of the plant's metal products on the global market is the transition to high-grade iron ore feedstock with low phosphorus content.

Studies conducted during the implementation of the technology for processing hot metal with reduced phosphorus content made it possible to identify optimal technological practices for achieving high technical, economic, and environmental performance depending on the phosphorus content in the processed hot metal.

In the case of hot metal containing 0.3 – 0.6 wt. % phosphorus, the use of a single-slag process resulted in low consumption of hot metal and lime, as well as reduced total emissions of dust and CO. However, this process did not ensure sufficiently low concentrations of phosphorus and sulfur in the final steel.

On the other hand, processing hot metal with less than 0.3 wt. % phosphorus using early intermediate slag tapping did not significantly improve technological performance, while worsening environmental indicators. This was due to increased CO and dust emissions caused by additional dust releases during converter turndown, compared to the single-slag process, and the inability to achieve complete CO afterburning at the flare due to process interruption during peak CO formation (Fig. 5).

An analysis of technical, economic, and environmental indicators for different hot metal processing methods – including the single-slag process (*A*), early intermediate slag tapping (*B*), and the traditional two-slag process (*C*) – showed that the most efficient and environmentally sound option is the single-slag process when phosphorus content in hot metal does not exceed 0.3 wt. % (Table 3).

When processing hot metal with elevated phosphorus content (above 0.3 wt. %), as well as high silicon (above 1.0 wt. %) and sulfur (above 0.03 wt. %) content, achieving low final concentrations of phosphorus and sulfur requires early removal of acidic slag at 7 – 9 min into the blow. This method results in increased emissions of dust and carbon monoxide (Table 3). Notably, CO emissions in this case are even higher than those observed in the traditional two-slag process, where the intermediate slag is removed after 65 – 75 % of the main blowing time. This is due to the interruption of blowing at the point of peak CO concentration (40 – 60 vol. %) and the inability to perform afterburning at the flare for safety reasons before resuming the blow (Fig. 5, *b*).

The duration of the afterburning period at the flare prior to atmospheric release is significantly reduced, resulting in most of the CO being emitted unburned.

In experimental heats conducted using method *A*, low dust emissions (0.305 t/heat) and carbon monoxide emissions (2.808 t/heat) were recorded, along with reduced lime consumption (71.8 kg/t) and oxygen consumption (63.4 m^3/t). Additionally, slag oxidation was reduced to 20.7 %, and a high prime yield of steel – 89.6 % – was achieved.

In developing the process for low-phosphorus hot metal conversion, all environmentally friendly converter steelmaking practices previously implemented for high-phosphorus hot metal were taken into account.

The resource-saving converter process includes retaining a portion of slag from the previous heat in an inactive state. This is achieved by adding lime or dolomite, as well

Table 3. **Technological and environmental indicators of hot metal conversion with different phosphorus content**

Таблица 3. **Технологические и экологические показатели передела чугунов с различным содержанием фосфора**

Indicators	Process option		
	A	*B*	*C*
Hot metal consumption, kg/t	817	814	823
Hot metal composition, wt. %:			
[Mn]	0.610	0.670	0.740
[Si]	0.800	0.890	0.830
[P]	0.217	0.450	0.481
[S]	0.033	0.032	0.027
Scrap consumption, kg/t	306	307	329
Lime consumption, kg/t	71.8	77.4	97.0
Oxygen consumption, m^3/t	63.4	63.1	69.0
Oxygen consumption [C], %:			
<0.04 wt. %	5.6	24.8	27.4
(FeO) content in slag, wt. %	20.7	21.2	21.2
Gross emissions per heat, t:			
dust	0.305	0.402	0.422
CO	2.808	6.260	4.421
Prime yield, %	89.6	89.1	86.8
Duration, min:			
blowing	20.3	21.6	22.7
heat	57.2	60.0	62.0
Slag output, kg/t	150	235	264

as pre-treated steelmaking slag, in an amount equivalent to 20 – 30 % of the total lime consumption per heat.

Lime is introduced in 2-ton portions during the blowing period. Approximately 30 – 40 s before each addition, the blowing intensity is reduced by 150 – 200 m^3/min, and subsequently restored to the previous level.

The bath is blown at reduced intensity following a specially developed dynamic mode. During the first 3 – 5 min, blowing is carried out at an intensity of 850 – 900 m^3/min, followed by a reduction to 650 – 750 m^3/min for the main stage of the blowing.

At the final stage of blowing, the lance is lowered to a height of 1.3 – 1.5 m, and the oxygen flow rate is increased to 850 – 900 m^3/min.

Reducing the phosphorus content in the hot metal to 0.3 wt. % decreases lime consumption from 143 to 77 kg per ton of steel. This reduction enables lower lime production volumes and allows decommissioning of some environmentally unfavorable lime kilns.

When working with low-phosphorus hot metal, the use of a single-slag process shortens the blowing and overall heat duration by 10 – 16 %, thereby increasing converter productivity.

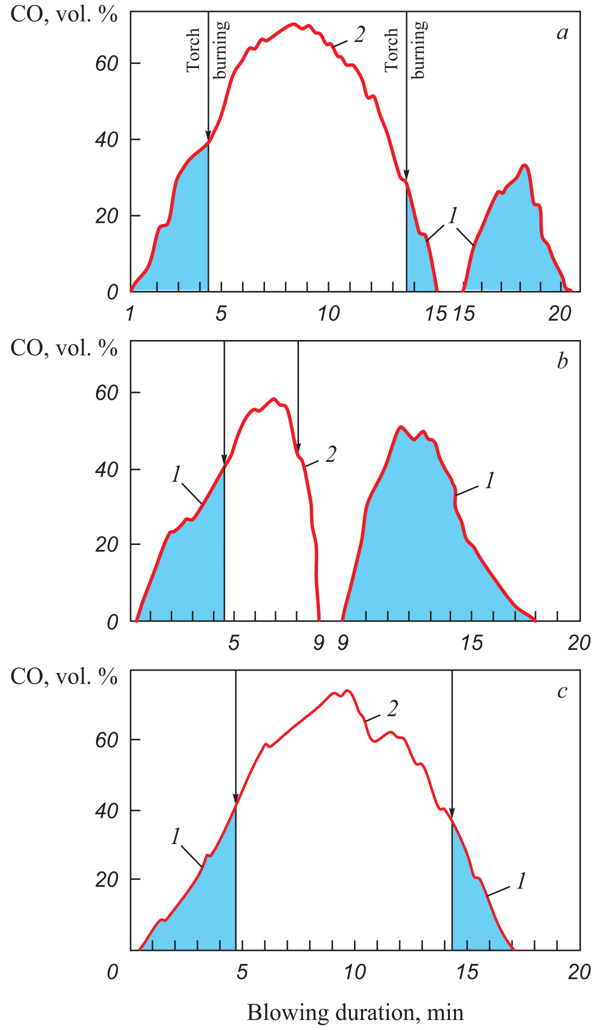

Fig. 5. Nature of change in CO emitting into the atmosphere with different versions of the converter smelting technology
a – by a two–slag process; *b* – with early slag discharge; *c* – by a single–slag process;
1 – emission of CO without afterburning on a flare;
2 – with afterburning of CO to CO_2 on a flare before emitting into the atmosphere

Рис. 5. Характер изменения выхода CO в атмосферу при различных вариантах технологии конвертерной плавки:
a – двухшлаковым процессом; *b* – с ранним скачиванием шлака;
c – одношлаковым процессом;
1 – выброс CO без дожигания на свече; *2* – с дожиганием CO до CO_2 на свече перед выбросом в атмосферу

Conclusions

The implementation of a resource-saving technology that retains the final slag from the previous heat in an inactive state – by adding pre-treated steelmaking slag – significantly reduces dust and gas emissions from the converter. This is achieved through the formation of an active foaming slag at the early stage of blowing and through reduced lime consumption during the heat.

Balancing the volume of converter off-gases with the gas duct system's throughput capacity allows for a 30 – 40 % reduction in dust emissions to the gas cleaning system and an 83 % reduction in disorganized emissions from under the converter skirt.

Peak dust emissions under the converter skirt during the addition of slag-forming materials are mitigated by reducing the blowing intensity 30 – 40 s before the addition and restoring it afterward.

CO emissions into the atmosphere are reduced by increasing the rate of CO concentration buildup to the flammability limit of moist converter gases in the early blowing stage, followed by afterburning at the flare before release into the atmosphere. Additionally, CO emissions are lowered by using a shortened first blowing period and ensuring a carbon content of 0.8 – 1.0 wt. % at the point of converter turndown.

Reducing the phosphorus content in the hot metal to 0.3 wt. % allows not only for decreased lime consumption (from 143 to 77 kg/t of steel), but also for shorter blowing and heat durations (by 10 – 16 %). This, in turn, enables a reduction in lime production and the shutdown of environmentally adverse calcination units, while also boosting converter productivity.

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Information about the Authors

Irshek K. Ibraev, *Dr. Sci. (Eng.), Prof. of the Chair "Metallurgy and Materials"*, Karaganda State Industrial University
ORCID: 0000-0002-6414-6901
E-mail: ibraevik@yandex.ru

Orazbike T. Ibraeva, *Cand. Sci. (Eng.), Assist. Prof.*, Karaganda State Industrial University
ORCID: 0000-0002-8490-1994
E-mail: ibraevaot@yandex.ru

Сведения об авторах

Иршек Кажикаримович Ибраев, *д.т.н., профессор кафедры «Металлургия и материаловедение»*, НАО «Карагандинский индустриальный университет»
ORCID: 0000-0002-6414-6901
E-mail: ibraevik@yandex.ru

Оразбике Токтархановна Ибраева, *к.т.н., доцент*, НАО «Карагандинский индустриальный университет»
ORCID: 0000-0002-8490-1994
E-mail: ibraevaot@yandex.ru

Contribution of the Authors

I. K. Ibraev – conceptualization, scientific guidance, editing the text, conducting industrial research.

O. T. Ibraeva – writing the text, performing thermodynamic calculations and laboratory experiments, processing and analyzing the results.

Вклад авторов

И. К. Ибраев – разработка концепции работы, научное руководство, редактирование текста статьи, проведения промышленных исследований.

О. Т. Ибраева – написание текста статьи, выполнение термодинамических расчетов и лабораторных экспериментов, обработка и анализ результатов.

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