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IMPROVING INDUSTRIAL AND ENVIRONMENTAL SAFETY WHEN IMPLEMENTING TECHNOLOGIES OF LIQUID-PHASE REDUCTION OF IRON OXIDES

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Abstract: *The article examines the main scientific and practical results of the research on improving the envi-ronmental safety of ironmaking processes through the implementation of liquid-phase iron oxide re-duction technologies. The current state of industrial and environmental safety in coke-based ironmak-ing using traditional technologies and production processes (coking, sintering, and blast furnace) is described. The results of a comparative analysis of hazardous production factors and harmful emis-sions into the environment from traditional ironmaking technologies and liquid-phase iron oxide re-duction technologies are presented. It is established that the implementation of the liquid-phase iron reduction technology eliminates numerous hazardous technological operations and reduces the envi-ronmental impact of metallurgical production. It is shown that the automation of liquid-phase reduc-tion processes excludes the presence of workers in zones of high temperatures, intense radiation, and other hazardous production factors. The research results can be applied when implementing alterna-tive nonblast-furnace iron production methods.*

Keywords: *hazardous production factors, harmful industrial emissions, environmental safety, ironmaking, liquid-phase iron oxide reduction*

1. The Problem and its Connection to Scientific and Practical Tasks

The full-scale blast furnace complex is one of the most hazardous facilities in the ferrous metallurgy industry in terms of occupational safety and environmental impact. The classical scheme of coke-based ironmaking that applies traditional technologies and production processes (coking, sintering, and blast furnace operations), involves a significant number of harmful and hazardous production factors that cannot be completely eliminated due to the specific nature of the technological processes [1, 2, 3]. High concentration of pollutants in industrial facilities and the environment, including dust, gas emissions, sludge, and other harmful substances, along with the increasing environmental requirements imposed on metallurgical enterprises, highlight the urgent need to modernize traditional ironmaking technologies. However, the modern development of blast furnace technology faces growing challenges inherent to all technical systems, necessitating the search for new approaches to ironmaking as an alternative to conventional blast furnace smelting. Therefore, the primary objective of modern ferrous metallurgy should be the transition toward green metallurgy standards, reducing occupational risks for workers, and increasing the productivity and competitiveness of ironmaking technologies in the global market.

2. Analysis of Recent Research and Publications.

The traditional scheme of coke-based ironmaking consists of a technological chain that includes coke production, iron ore pelletizing, and the blast furnace process. At each stage of production, working conditions are recognized as hazardous and harmful, while the volume of environmental pollutants makes traditional metallurgical production one of the most ecologically dangerous industries.

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Coke chemical production is one of the most hazardous stages in terms of both industrial and technogenic safety due to the use of highly toxic, explosive, and aggressive chemical substances, as well as complex technological operations. These processes involve working in confined spaces, exposure to high temperatures, physical exertion, hazardous microclimatic conditions, and interactions with gases and heavy machinery [4, 5].

Chemical risks associated with coke chemical production stem from the release and utilization of highly toxic substances such as hydrogen sulfide (H_2S), ammonia, benzene, acetone, and sulfur oxides. The technological processes inevitably generate these emissions, as these substances are naturally present in coal. Even at low concentrations, they pose severe health risks, causing poisoning and respiratory irritation, and with prolonged exposure, they may lead to cancer or even death.

A comparison of the maximum allowable concentrations (MAC) of carcinogenic emissions from coke chemical production, as established by national and international organizations such as OSHA (USA), EU-OSHA (EU), and national sanitary services (e.g. the State Sanitary Service of Ukraine), along with actual emission data from coke chemical production, is presented in Table 1.

Table 1. Comparison of Maximum Allowable Concentrations (MAC) of Carcinogens in Coke Chemical Production

Carcinogen	**MAC, mg/m^3**	**Actual concentration, mg/m^3**	**Notes**
Benzene	0.1 – 1	1.0 – 5.0	Depends on the country: EU – 0.5 mg/m^3 USA – 1 mg/m^3
Formaldehyde	0.1 – 0.5	0.5 – 2.0	EU – 0.37 mg/m^3 USA – 0.75 mg/m^3
Chromium (VI) compounds	0.001 – 0.005	0.01 – 0.1	EU – 0.005 mg/m^3 USA – 0.001 mg/m^3
Nickel and its compounds	0.005 – 0.1	0.01 – 0.5	Depends on the specific compound, e.g. nickel carbonate – 0.001 mg/m^3
Arsenic	0.01 – 0.05	0.05 – 0.2	EU – 0.01 mg/m^3 USA – 0.01 mg/m^3
Benzo(a)pyrene	0.0001 – 0.001	0.001 – 0.01	EU – 0.0001 mg/m^3 Ukraine – 0.00015 mg/m^3

In addition to the aforementioned highly toxic substances, the coking process also generates explosive gas mixtures: methane-air, hydrogen-air, light hydrocarbon gases-air, and hydrogen sulfide mixtures. Their high sensitivity to temperature fluctuations and even minor sparks necessitates stringent monitoring of their concentration in the air across various production areas.

Working in confined spaces while maintaining and repairing equipment, e.g. inside tanks, pipelines, manholes etc., increases the risk of poisoning and other accidents due to poor ventilation and/or oxygen displacement by toxic gases. Moreover, work in confined spaces is complicated by physical factors such as restricted mobility, poor visibility, and difficult access, which hinder evacuation in case of danger and create risks of injuries due to falls or contact with sharp or hot surfaces.

High air temperatures at coke-chemical plants, particularly near coke ovens, where summer temperatures can reach 60–100°C, increase risks of overheating and heat strokes.

Sintering production is characterized by a high level of air dustiness due to the processing of bulk materials. This factor poses significant health risks to workers, as fine particulate dust penetrates the respiratory system, causing chronic lung diseases. For instance, in the ore yard during raw material unloading, dust levels can reach 12–46 mg/m^3, significantly exceeding the maximum allowable value of 4 mg/m^3. In material distribution, crushing, grinding, and mixing departments, dust concentrations ~~range from~~ make 65–180 mg/m^3, 60–600 mg/m^3, and 16–100 mg/m^3 respectively [6, 7].

The operation of crushers, screens, feeders, mixers, and other equipment generates high noise levels, ranging from 98 to 115 dBA, which significantly exceed sanitary standards and may lead to hearing loss, stress, and chronic fatigue among workers [8].

In the sintering zone, the primary piece of equipment is the sintering machine, which contains moving, rotating, and high-temperature parts. Additionally, combustion byproducts such as carbon monoxide and sulfur dioxide are released into the workspace, posing a poisoning risk to workers by adversely affecting the respiratory and cardiovascular systems, as well as overall health, causing headaches, weakness, and mucous membrane irritation. The intensity of thermal radiation at workplaces reaches 0,35–2 kW/m^2, far exceeding the standard limit

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of 0.14 kW/m², increasing the risk of worker overheating, heat strokes, and decreased productivity. High temperatures, low humidity, and strong airflows further affect workers' efficiency and health.

The machine unloading zone, which is the main source of dust, gas, and thermal radiation emissions, is separated from other areas by a wall. Here, extremely high dust levels are observed when the sinter cake is dropped onto the grizzly, reaching 160–1300 mg/m³. However, the highest dust emissions occur during sinter sorting — 5000 mg/m³ — and loading it into railcars, where concentrations are measured in g/m³, reaching 2.5–4.9 g/m³. The total dust emissions from the entire technological process can reach 3360 kg/h. To minimize dust emissions in this area, sealed enclosures connected to dust and gas extraction systems are installed. However, while this reduces dust emissions, it does not ensure the required air purity [6, 7].

Near the blast furnace, which integrates complex technological processes and mechanical operations, major hazardous production factors include intense dust emissions, noise, and vibration – typical hazards in areas with ore and coke bunkers, screens, skip hoists, etc. Additional risks specific to blast furnace operations include intense thermal and infrared radiation in the casting yard, near the iron and slag runners in particular, the blast furnace gas and its pressure in pipelines, the small bell, and air ducts. Mechanical hazards also arise from unprotected moving parts of production equipment, rotating machine components, and other mechanisms.

The bunker trestle is one of the primary dust emission sources in the blast furnace shop. During storage, homogenization, and transportation of ore and other blast furnace charge components, significant dust emissions occur: 200–421 mg/m³ in winter and up to 589 mg/m³ in warm periods [9, 10].

The air and surfaces of stockhouses also become contaminated with dust. Dust accumulates on building structures and equipment at a rate of 3–34 kg/m² per day, and over the scale-car pockets— up to 20 kg/m² per day. Specific dust emissions in the stockhouse area equipped with scale cars average 2.5–3.5 kg per 1t of iron produced.

From a technological standpoint, a crucial area in blast furnace production is the casting yard –an indoor facility equipped for tapping molten iron and slag from the blast furnace. In addition to powerful thermal and infrared radiation, with an intensity of 2–18 kcal/cm² per minute; contaminated air, which contains toxic and dangerous gases and dust, also adds to hazardous and harmful working conditions in the casting yard.

Key air pollutants in the casting yard include carbon monoxide, with concentrations reaching 23.5 mg/m³ (exceeding the limit of 20 mg/m³), sulfur dioxide (SO_2) at 16.8 mg/m³ (exceeding the limit of 10 mg/m³), which are released mainly during iron tapping, slag tapping and smelting, as well as dust at 18.5 mg/m³ (far above the limit of 4.0 mg/m³). This dust is generated during the preparation of iron and slag runners and the evaporation of molten products, containing metal and graphite particles. During iron tapping, dust concentration near the runner can reach 270 mg/m³. This dust contains iron oxides (up to 57%), silicon dioxide (up to 29%), and carbon in the form of graphite (up to 7%), exhibiting fibrogenic effects [8, 9].

Other hazardous factors affecting casting yard workers include elevated sound pressure levels of 86 dBA (exceeding the permissible 80 dBA) and increased surface vibration with a velocity of 2.5–4 mm/s, observed during the movement of mechanical equipment and oxygen lance blowing. [8].

3. Problem Statement

The rapid tightening of environmental regulations faced by numerous metallurgical plants worldwide is driving the development and transition from traditional coke-based metallurgy to cleaner, non-blast furnace ironmaking methods. Such an approach to ironmaking can be exemplified in the implementation of liquid-phase iron oxide reduction technologies, which have successfully undergone testing and are being applied by metallurgical plants globally [11, 12].

4. Presentation of the Material and Results

The equipment complex for coke-free ironmaking using ore concentrate and coal is similar to that of sintering furnaces. As a result, most of the fugitive emissions typical of sintering operations will also be characteristic of liquid-phase iron oxide reduction (Fig. 1) [11, 12].

Air pollution in the ore yard and preparation departments is one of the most pressing concerns for the studied technology due to several key factors. The primary reason is the large number of technological operations that are sources of dust emissions, including transportation, crushing, screening, mixing, and storage of ore and coal materials. Ore yards are often open-air facilities, which exacerbates the impact of weather conditions (wind, humidity) on dust formation.

In indoor facilities, such as charge material preparation departments, dust levels remain high due to the insufficient efficiency of ventilation systems and the inability to install them in certain areas. During crushing, grinding, and screening operations in these sections, fine particles easily become airborne, even despite availability of dust containment and removal equipment (aspiration systems).

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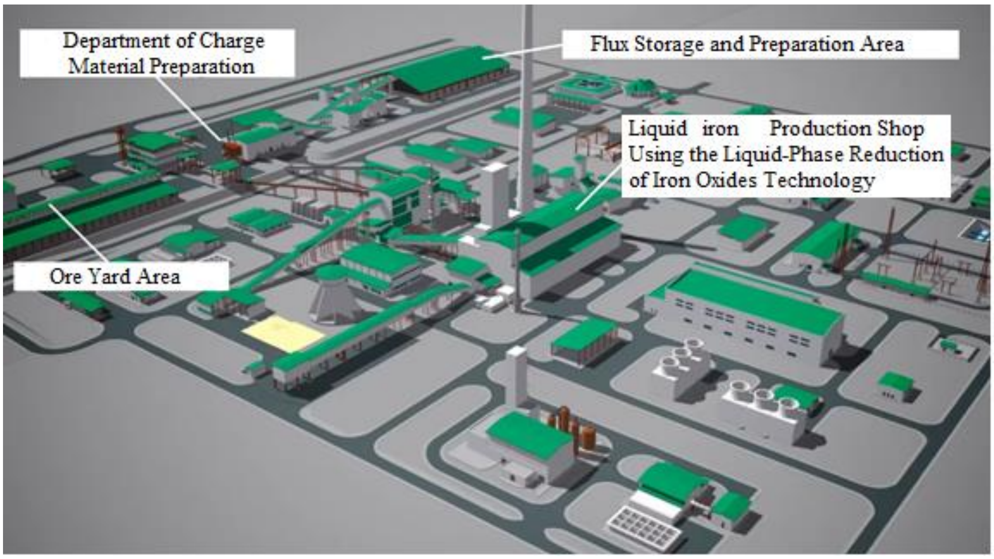

Fig.1. Three-dimensional model of a complex for the liquid-phase reduction of iron oxides

Additionally, the scale of production plays a crucial role, as this unit typically processes vast amounts of raw materials, making dust generation inevitable. Therefore, the most effective dust control measures include installing protective enclosures on crushers and screens, connecting them to aspiration systems, and implementing specialized enclosed conveyor galleries to transport materials directly from the preparation area to the smelting unit.

Among other hazardous industrial factors associated with the liquid-phase reduction of iron oxides, thermal and infrared radiation should be highlighted. Its intensity is comparable to that of blast furnaces. However, unlike in the case of blast furnaces, metal tapping can be performed fully automatically, minimizing or completely eliminating the presence of workers in high-temperature zones, areas of intense heat radiation, and other hazardous conditions in the casting yard. Moreover, an improved heat dissipation system reduces the working area temperature near the unit at a distance of 3–5 meters to 0.5–1.0 kW/m^2**,** whereas for a blast furnace, this value is 1.0–1.5 kW/m^2 (Fig. 2 and Fig. 3).

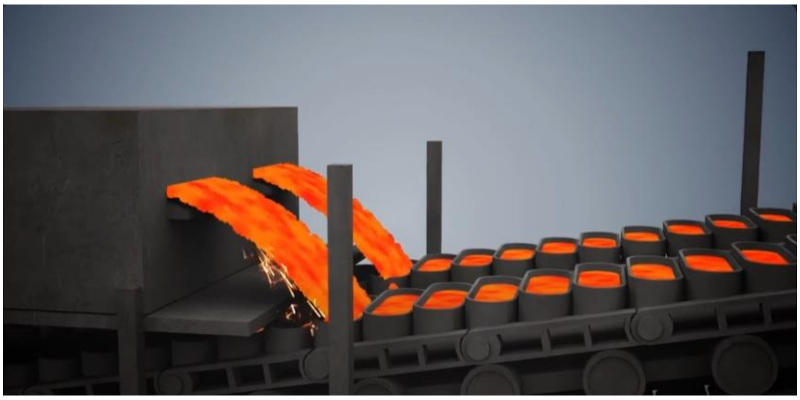

Fig.2. Three-dimensional modeling of the system of liquid iron tapping from the smelting unit

Fig.3. Three-dimensional model of the conveyor for transporting liquid iron

During metal discharge, harmful gases are released, including carbon monoxide (CO), carbon dioxide (CO_2), and sulfur dioxide (SO_2) [9]. In the liquid-phase reduction process, the concentration of harmful gases in emissions is lower compared to the blast furnace process. For instance, SO_2 levels in gas emissions during liquid-phase reduction range from 20 to 50 mg/m³**,** whereas for a blast furnace, they range from 65 to 100 mg/m³**.** However, in some cases, the concentration of certain harmful gases in emissions from the liquid-phase reduction process exceeds that of blast furnace smelting. For example, nitrogen oxides (NO_x) emissions can reach 300 mg/m³ in liquid-phase reduction, whereas in blast furnace smelting, NO_x emissions are minimal due to the absence of direct combustion. Additionally, during metal and slag tapping, a certain amount of dust is released, which is approximately the same for both processes, ranging from 30 to 50 mg/m³**.**

The sound pressure level in the working area during the operation of liquid-phase reduction smelting units reaches 80–100 dBA, while directly near the reactor, noise levels can increase to 105–110 dBA, which is comparable to the noise levels of a blast furnace **(**86–110 dBA**).** The surface vibration velocity generated by the lance blowing process in the reaction zone of a liquid-phase reduction unit is 1.5–2 mm/s, whereas for a blast furnace, this value is 2.5–4.0 mm/s**.**

Given the nature and sources of emissions, it is evident that the liquid-phase reduction process for iron oxides shares similarities with sintering and blast furnace production. The primary challenges of this technology include dust emissions during technological operations, primarily in ore yards and charge material preparation departments. Gas emissions and the intensity of thermal radiation during metal discharge are also integral factors in ironmaking. However, process automation allows for minimizing human presence in hazardous work areas where conditions are classified as harmful and dangerous.

Overall, liquid-phase reduction processes offer advantages in environmental and ergonomic aspects. However, further improvements are needed in dust emission containment, ventilation systems in production facilities, and noise reduction to minimize adverse health effects on workers.

Additionally, a comparison of emissions into the environment is conducted for the traditional sinter-coke-blast furnace cycle and the liquid-phase reduction cycle, assuming the same production volume within a metallurgical plant with a closed water circulation system (Table 2).

Table 2. Emissions of Pollutants in Metallurgical Production

Emission Source	**CO_2, kg/t of product**	**Dust Emissions, kg/t of product**	**Content of Chemical Compounds in Off-Gases, %**		
			SO_2	**NO_x**	**CO**
Coke Plant	250–350	8–16	0.3–1.0	0.1–0.4	0.1–0.5
Sintering Plant	150–250	0.4–1.3	0.1–0.5	0.3–0.8	0.5–1.5
Blast Furnace	1600–2000	0.2–0.7	0.05–0.2	0.1–0.4	15–25
Liquid-Phase Reduction Process	600–800	0.1–0.5	0.02–0.1	0.05–0.2	1–3

Results of the analysis are plotted in Figure 4.

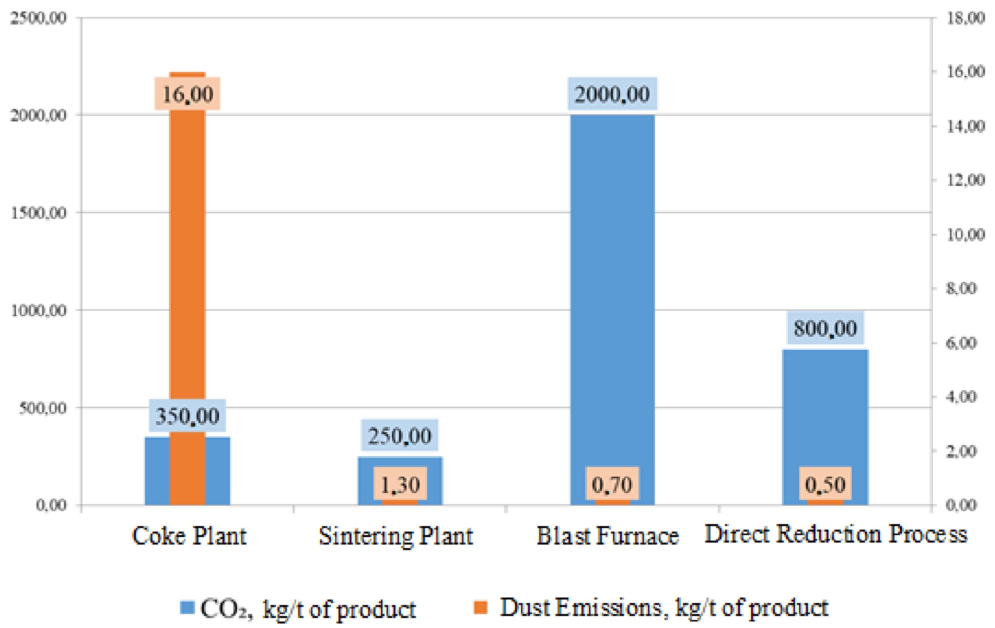

Fig.4. Emission Diagram of Metallurgical Enterprises for the Production of 1t of Product

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In this case, environmental pollution differences are determined solely by emissions of solid and gaseous substances into the atmosphere, as well as by the volumes of storage for iron-containing waste mixed with non-ferrous metal impurities.

The blast furnace process relies on coke combustion, which releases significant amounts of carbon dioxide (CO_2), sulfur oxides (SO_x), nitrogen oxides (NO_x), along with dust and other harmful substances. Sulfur and nitrogen oxides contribute to acid rain, which adversely affects the environment by altering soil acidity in adjacent areas. This effect harms local flora and fauna, reducing biodiversity and leading to ecosystem degradation. Toxic heavy metals, which may also be released during the blast furnace process, accumulate in plants and enter the food chain, ultimately harming animals.

The liquid-phase reduction of iron oxides represents a more advanced technology for processing iron ore raw materials without coke, using pulverized coal or coal dust instead. The elimination of iron ore sintering and coal coking significantly reduces CO_2 emissions into the environment. Under normal operating conditions, CO_2 concentration in the reactor outlet can exceed 70%, while the remaining 30% consists mainly of nitrogen from carrier gases used for ore and coal injection.

Generation of SO_x is primarily determined by the sulfur content in coal and raw materials, allowing adjustments in CO_2 and sulfur oxide emissions. Additionally, the gas purification system in the liquid-phase reduction process includes an adsorber with a lime slurry, which reduces SO_x emissions by a factor of 411. The formation and emission of nitrogen oxides and CO in this process are lower by factors of 3.5 and 80 respectively, mainly due to the absence of sintering production.

In the liquid-phase reduction plant, approximately 90% of dust emissions occurs within the working space of the unit and the raw material loading zone, in contrast to the sintering-coke-blast furnace route, which has numerous unorganized, spatially dispersed emissions. Depending on the expected chemical composition of off-gases, the purification system includes various gas cleaning devices: cyclones for removing coarse dust at the first stage, electrostatic precipitators for fine particle filtration, scrubbers (both wet and dry) for desulfurization and acid gas removal, and catalytic converters for CO to CO_2 conversion. As a result, dust emissions into the environment are 811 times lower than in the blast furnace cycle, while total emissions are reduced by a factor of 711, excluding highly toxic emissions from coke-chemical production.

5. Conclusions

The analysis of research on liquid-phase reduction processes in the ferrous metallurgy sector indicates that eliminating coke production and iron ore sintering technologies allows compliance with established environmental regulations. Additionally, it reduces workplace injuries and occupational disease risks, improves working conditions for production personnel, ensures process safety, and achieves economically favorable outcomes.

The implementation of the liquid-phase iron oxide reduction technology removes hazardous, highly polluting, and energy-intensive coke and sinter (pellet) production from the technological chain. This significantly reduces the environmental footprint of metallurgical production, eliminates numerous dangerous technological operations, decreases the overall amount of environmental pollutants, and reduces harmful dust and gas emissions, as well as other industrial hazards.

Automation of liquid-phase reduction processes eliminates the need for workers to operate in high-temperature zones, intense radiation areas, and other hazardous production environments. This substantially lowers the risks of workplace injuries and occupational diseases.

The economic benefits of the liquid-phase iron reduction technology include reduced costs for raw material procurement and energy consumption. Additional advantages of this technology include the possibility of industrial and/or household waste disposal, thus contributing to recycling and environmental sustainability efforts.

Overall, coke-free iron metallurgy demonstrates significant environmental and economic advantages, particularly in reducing harmful emissions and the storage volumes of waste containing heavy metals, leading to lower ironmaking costs. However, to further minimize the negative impact of hazardous production factors on workers' health, it is necessary to improve dust containment and ventilation systems in production facilities, as well as enhance worker protection from noise exposure during the maintenance of smelting units.

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