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Original article
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Modeling the distribution of components emitted from oiled scale between water, gas, and dust media in blast furnace dedusting plant

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Abstract. Distribution of oil from oiled scale between various types of waste from blast furnace dedusting plant: dust, sludge, and slime water was estimated by physical modeling using a vertical tubular electric furnace. According to the mathematical modeling of thermal state of a metal container with oiled scale, intensive evaporation of oil in a blast furnace begins after it is loaded and lowered along the shaft to a depth approximately corresponding to three feeds. The oil was passed through a layer of sinter and pellets of the Mikhailovsky GOK heated to 500 °C with a mass of 0.6 kg and a particle size of 10 – 12 mm. Together with oil vapors, finely ground material was injected into the layer of iron ore raw materials (IORM), which imitated in component and fractional composition a mixture of blast furnace dust and sludge from a vacuum filtration plant (VFC) of blast furnace shop, taken in a ratio of 36:64. The physical modeling ensured compliance with the actual gas-dynamic mode in the area of blast furnace ore ridge, based on equality of the Reynolds criterion. The value of this criterion, equal to 215, was achieved in the laboratory model when argon was supplied with a flow rate of 70 L/min. According to the experimental results, distribution of oil was, % of the initial amount: 74.8 % decomposed on the IORM layer corresponding to three feeds; 9.1 % turned into blast furnace dust; 15.9 % turned into VFC sludge; there was no oil in the wet gas purification water; 0.2 % (30 mg) of the oil underwent wet dedusting in the form of an aerosol; a small amount of soot was observed on the pipeline walls. Gas phase of oil decomposition contained: 70 – 90 % H_2; 1.5 % CO; 0.5 – 7.0 % CO_2; 3.2 – 22.2 % CH_4; 0.1 – 2.5 % Σ(C_2H_4, C_2H_6, C_3H_6, C_3H_8). The content of benzo(a)pyrene controlled in Russia in oil vapor did not exceed 0.00058 %.

Keywords: technogenic waste disposal, oiled scale, recycling methods, oil evaporation, blast furnace

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Моделирование распределения компонентов, выделившихся из замасленной окалины, между водо-газо-пылевыми средами системы газоочистки доменной печи

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Аннотация. Физическим моделированием с использованием вертикальной трубчатой электропечи оценили распределение масла из замасленной окалины между различными видами отходов газоочистки доменного производства: пылью, шламом и шламовой водой. Согласно математическому моделированию теплового состояния металлического контейнера с замасленной окалиной интенсивное испарение масла в доменной печи начинается после его загрузки и опускания вдоль шахты на глубину, примерно соответствующую трем подачам. Масло пропускали через нагретый до 500 °С слой агломерата и окатышей Михайловского ГОК массой 0,6 кг и крупностью частиц 10 – 12 мм. Вместе с парами масла в слой железорудного сырья (ЖРС) подавали (вдували) тонко измельченный материал, имитиро-

вавший по компонентному и фракционному составам смесь колошниковой пыли и шламов вакуумной фильтровальной установки (ВФУ) доменного производства, взятых в соотношении 36:64. Физическое моделирование обеспечивало соответствие фактическому газодинамическому режиму в зоне рудного гребня доменной печи, исходя из равенства критерия Рейнольдса. Значение этого критерия, равное 215, было достигнуто в лабораторной модели при подаче аргона с расходом 70 л/мин. По результатам эксперимента распределение масла составило, % от исходного количества: 74,8 % разложилось на слое ЖРС, соответствующем трем подачам; 9,1 % перешло в колошниковую пыль; 15,9 % перешло в шлам ВФУ; в воде мокрой газоочистки масло отсутствовало; 0,2 % (30 мг) масла проходило мокрую газоочистку в форме аэрозоля; на стенках трубопровода наблюдалось незначительное количество сажи. Газовая фаза процессов разложения масла содержала: 70 – 90 % H_2; 1 – 5 % CO; 0,5 – 7,0 % CO_2; 3,2 – 22,2 % CH_4; 0,1 – 2,5 % Σ(C_2H_4, C_2H_6, C_3H_6, C_3H_8). Содержание контролируемого в России бензо(а)пирена в парах масла не превышало 0,00058 %.

Ключевые слова: утилизация техногенных отходов, замасленная окалина, методы переработки, испарение масла, доменная печь

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Introduction

Improving the environmental performance of ferrous metals production and processing increasingly rely on recycling technogenic waste back into production [1; 2]. Among the most valuable iron bearing waste products generated at ferrous metallurgy plants is oiled scale from rolling mills [3 – 5]. This material consists almost entirely of iron oxides (with an iron content of 69 – 72 %) and contains virtually no gangue [6; 7]. Two main types of rolling scale are distinguished, differing in particle size and oil content. The coarse fraction (+2 mm), which accounts for up to 70 – 80 % of the total scale, contains less than 3 % oil and can be effectively used in the sinter burden. The fine fraction (particles smaller than 100 μm) contains a much higher oil content (up to 20 – 30 %), which makes its use in sintering more problematic. During sintering of a burden with elevated oil content, unburned oil residues evaporate, forming explosive mixtures in the oxidizing zones of the sinter machine gas tract. After condensation, the oil contaminates the exhauster blades, reducing their service life [8].

Alternative utilization methods for oiled rolling scale include preliminary chemical treatment (washing with alkali and surfactant solutions) [9; 10] or preliminary thermal treatment (rotary kilns, thermostats, mixers) [11; 12]. The de oiled product is then processed through sintering [14; 15] or briquetting [16]. However, these approaches have not been implemented on an industrial scale due to techno economic constraints, and the problem remains unresolved.

A more recent alternative to the multistage and costly preparation of oiled scale for blast furnace smelting – via sintering or briquetting with prior de oiling – is the direct charging of oiled scale into the blast furnace [17; 18]. According to a patented method [17], instead of using low strength briquettes, oiled scale can be placed in a metallic container designed to melt at temperatures of at least 1500 °C. This approach requires minimal additional equipment, shortens preparation time, eliminates the need for separate storage and disposal of extracted organic compounds, and avoids the purification of contaminated circulating water. However, when granulated oiled scale is charged into the blast furnace, incomplete decomposition of oil vapors passing through the burden may complicate the operation of the furnace dedusting system [19]. Therefore, it is important to evaluate how the oil contained in oiled scale affects the composition of blast furnace dust, VFC sludge, slime water, and the formation of the gas phase in blast furnace off takes.

Materials and methods

In this study, the distribution of oil among various types of blast furnace dedusting wastes (dust, sludge, and slime water) was investigated by physical modeling in a vertical tubular electric furnace. A heated layer of sinter and pellets from the Mikhailovsky GOK, with a particle size of 10 – 12 mm and a mass of 0.6 kg, was successively charged together with a mixture that reproduced, in component and fractional composition, blast furnace dust and sludge from the vacuum filtration plant (VFC) in a ratio of 36:64.

The iron ore raw materials (IORM) were placed in the isothermal zone of the furnace. Their mass was determined from calculations of the amount of material located above the horizon of intensive oil evaporation in the furnace. According to mathematical modeling of the thermal state of a metal container with oiled scale, intensive oil evaporation in the blast furnace begins after the container is charged and lowered along the shaft to a depth corresponding to approximately three feeds. Consequently, the oil vapors pass through a layer of IORM roughly equal in height to three feeds [20 – 22].

To generate a gas flow in which mixing of dust and oil occurred, high grade argon (99.987 %) in accordance with GOST 10157–2016 was supplied at a rate of 70 L/min. This provided a Reynolds criterion value corresponding to the actual gas dynamic mode in the burden ridge zone of the blast furnace. At the furnace outlet, a bottle for “dry” dust collection was installed to simulate the cyclone dedusting unit, followed by a bottle with water for “wet” sludge collection, representing wet gas purification in scrubbers (see Figure).

The parameters of gas and material movement in the laboratory installation were modeled to reflect the following blast furnace operating conditions:

– average daily IORM consumption – 6278 t;

– pellet share in IORM – 36 %;

– average daily consumption of oiled scale (1 % of IORM mass) – 63 t;

– average daily pig iron production – 3798 t;

– average daily top gas generation – 7,139,563 nm^3;

– oil content in oiled scale – 15 %;

– oil mass in oiled scale – 9.4 t;

– water content in oiled scale – 10 %;

– water mass in oiled scale – 6.3 t;

– IORM mass per feed – 39 t;

– blast furnace dust yield – 4.6 kg/t hot metal;

– VFC sludge yield – 8.1 kg/t hot metal.

The component composition of dust used in the laboratory experiments was as follows:

1. Blast furnace dust (36 % of total mass):

– fractional composition: 10 % of class 1 – 3 mm and 90 % of class 0 – 1 mm;

– component composition:

– 75 % IORM mixture (64 % sinter and 36 % pellets);

– 25 % coke dust.

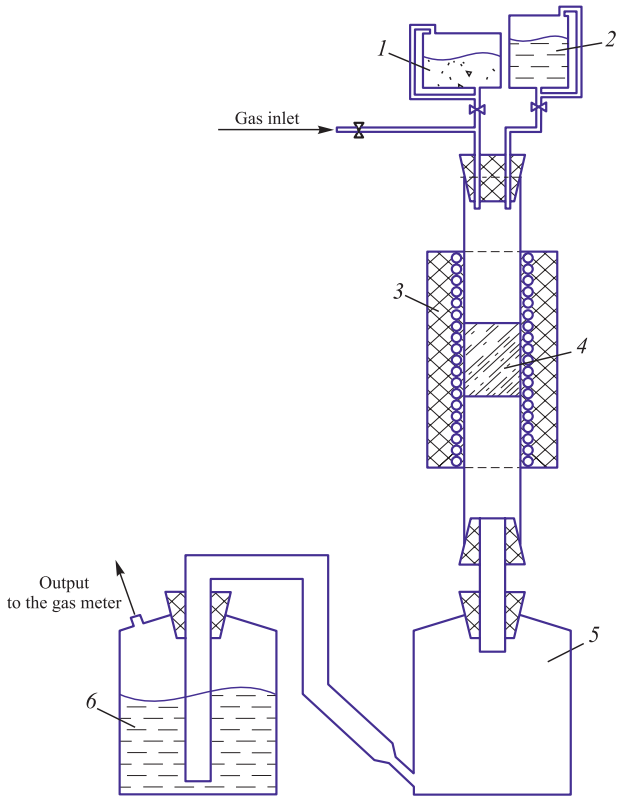
2. Sludge fraction (64 % of total mass):

– fractional composition: 100 % of class 0 – 0.2 mm;

– component composition:

– 75 % IORM mixture (64 % sinter and 36 % pellets);

– 25 % coke dust.



Scheme of experimental installation for physical modeling of the effect of oil on composition of blast furnace dust, sludge and water:
1 – dust bunker; *2* – oil bunker; *3* – laboratory electric tubular furnace; *4* – layer of iron ore raw materials; *5* – bottle for "dry" dust collection; *6* – bottle for "wet" sludge collection

Схема экспериментальной установки для физического моделирования влияния масла на состав колошниковой пыли, шлама и воды:
1 – резервуар с пылью; *2* – резервуар с маслом; *3* – лабораторная электрическая трубчатая печь; *4* – слой железорудного сырья; *5* – емкость для «сухого» улавливания пыли; *6* – емкость с водой для «мокрого» улавливания шлама

During the study, gas samples were taken and analyzed for the content of monoatomic, diatomic, and triatomic gases, as well as light hydrocarbons, using a Chromatec Crystal 5000 gas chromatograph system. For analysis, a packed column HayeSep Q (3 m) and a packed column NaX (3 m) with a Carboxen precolumn (0.5 m) were employed.

Oil samples were also taken to determine the content of seven polynuclear aromatic hydrocarbons (PAHs) – fluorene, phenanthrene, anthracene, fluoranthene, pyrene, chrysene, and benzo[a]pyrene – included in the list of 16 PAHs classified by the US Environmental Protection Agency (US EPA) as priority pollutants. Chromatographic analysis of the oil was carried out using a capillary column CR-5ms (5 % diphenyl/95 % dimethyl (polysiloxane)), 30 m × 0.32 mm × 0.25 μm.

Results

Calculated parameters of the laboratory study:

Oil mass for simulating vapor filtration through the IORM layer, corresponding to one feed, g	0.3
Gas volume required for one feed, based on the oil vapor fraction in blast furnace top gas, L	228
Duration of oil injection corresponding to one feed, min	3
Dust mass loaded into the laboratory installation corresponding to one feed, g	1.5
Reynolds number, Re	215
Number of feeds in the laboratory installation	50

To determine the oil content, thermogravimetric analysis was performed on the collected dust and sludge samples by heating them in an argon atmosphere. Weight losses were 5.2 % for dust and 4.9 % for sludge. With

a dust-to-sludge ratio of 36:64, the overall oil content in the samples after testing was 5.0 %.

Water evaporation from bottle 6 after the experiment showed no significant oil in the aqueous phase. The oil aerosol concentration after wet scrubbing was determined from a vapor–gas sample collected with an NP ZM sampling pump in accordance with GOST R 51945–2002, using indicator tubes for oil aerosols.

Based on the laboratory experiments, the oil distribution was as follows (percent of the initial oil content):

– 74.8 – decomposed in the IORM layer equivalent to three batches;

– 9.1 – transferred to blast furnace dust;

– 15.9 – incorporated into vacuum filtration sludge;

– 0.2 (30 mg) – passed through wet gas cleaning as aerosol.

A small amount of soot was observed on the inner walls of the pipeline during the experiments. No oil was detected in the wet gas purification water, indicating that nearly all of it was adsorbed by suspended fine coke dust particles, which were subsequently filtered, dried, and incorporated into the vacuum filtration sludge. Under industrial conditions, this process would simplify the treatment of recirculating water.

The chemical composition of the gas phase containing oil decomposition products was also analyzed. Across different gas samples, the concentrations of the main components were within the following ranges: 70 – 90 % H_2; 1 – 5 % CO; 0.5 – 7.0 % CO_2; 3.2 – 22.2 % CH_4; 0.1 – 2.5 % Σ (C_2H_4, C_2H_6, C_3H_6, C_3H_8). The formation of these gas components is associated with three main oil decomposition pathways:

1 – (catalytic) dehydrogenation of oil hydrocarbons with cleavage of C–H bonds, producing hydrogen gas and unsaturated compounds prone to polymerization and oxidation. This process is promoted by calcium, iron, and manganese oxides;

2 – (catalytic) cracking of oil hydrocarbons with cleavage of C–C bonds, producing lower molecular weight hydrocarbons, including gaseous hydrocarbons such as methane, ethane, propane, and butane. This process is strongly promoted by complex silicates and aluminosilicates in the agglomerate binder, such as pyroxenes and olivines.

3 – reduction of iron oxides with the formation of CO and CO_2, which is intensified at higher temperatures and when using iron ore raw materials with higher reducibility.

Analysis of oil samples for polynuclear aromatic hydrocarbons (PAHs) showed that the concentration of benzo[a]pyrene, which is regulated in Russia, did not exceed 0.00058 % in oil vapors.

Conclusions

An experimental assessment was conducted to evaluate the distribution of oil from oiled scale among different types of blast furnace dedusting plant – dust, sludge, and slime water – through physical modeling in a vertical tubular electric furnace. A mixture of sinter and pellets of the Mikhailovsky GOK (particle size 10 – 12 mm, mass 0.6 kg) was used to simulate, in terms of component and particle-size composition, blast furnace dust and vacuum filter sludge in a 36:64 ratio. When passing through a layer of iron ore raw materials (IORM) heated to 500 °C, 74.8 % of the oil decomposed within the IORM layer corresponding to three feeds; 9.1 % was transferred to blast furnace dust; and 15.9 % entered the vacuum filter sludge. Only 0.2 % of the oil underwent wet dedusting in the form of an aerosol, while no oil was detected in the wet gas purification water.

The gas phase of oil decomposition contained 70 – 90 % H_2; 1 – 5 % CO; 0.5 – 7.0 % CO_2; 3.2 – 22.2 % CH_4; 0.1 – 2.5 % Σ (C_2H_4, C_2H_6, C_3H_6, C_3H_8). A small amount of soot was observed on the pipeline walls, suggesting the possibility of soot deposition in blast furnace off-gas ducts.

Characteristics and content of polynuclear aromatic hydrocarbons in the oil vapor condensate sample

Характеристики и содержание полиядерных ароматических углеводородов в пробе конденсата паров масла

Substance	Fluorene	Phenanthrene	Anthracene	Fluoranthene	Pyrene	Chrysene	Benzo[a]pyrene
Molecular formula	$C_{13}H_{10}$	$C_{14}H_{10}$	$C_{14}H_{10}$	$C_{16}H_{10}$	$C_{16}H_{10}$	$C_{18}H_{12}$	$C_{20}H_{12}$
Molecular weight, a.u.	166	178	178	202	202	228	252
Boiling point, °C	294	340	340	382	402	448	495
IARC carcinogenicity classification*)	3	3	3	3	3	2B	1
Content in sample, %	$8.0 \cdot 10^{-5}$	$5.6 \cdot 10^{-2}$	–	$7.9 \cdot 10^{-5}$	$7.2 \cdot 10^{-5}$	$3.0 \cdot 10^{-4}$	$5.8 \cdot 10^{-4}$
*IARC – International Agency for Research on Cancer.							

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S. K. Sibagatullin – carrying out calculations, obtaining results, obtaining drawings and graphs.
A. V. Dzyuba – description of results, formulation of conclusions, critical analysis of literature.

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