Ecology and rational use of natural resources / **Экология и рациональное природопользование**

UDC 669.531.5
DOI 10.17073/0368-0797-2026-1-14-22

Original article
Оригинальная статья

REMOVAL OF CHLORINE FROM ELECTRIC ARC FURNACE DUST BY STATIC WASHING WITH WATER*

E. V. Grigor'ev, Yu. E. Kapelyushin, A. G. Ryazanov,
A. Bil'genov, D. V. Stepanov, A. A. Khalikulov

South Ural State University (76 Lenina Ave., Chelyabinsk 454080, Russian Federation)

grigorevev@susu.ru

Abstract. Electric arc furnace (EAF) dust is a complex multi-component waste of metallurgical industry, containing such valuable elements as iron and zinc. However, in addition to iron and zinc, EAF dust can be contaminated with various impurities, in particular chlorine, which complicates its subsequent processing. The authors investigated the possibility of chlorine removal from EAF dust by static washing with water. The main parameters are washing time, temperature mode, solid-to-liquid ratio, as well as the possibility of reuse of the waste water after washing. During the research, the optimal values of these parameters were determined: washing time of 1 h, solid to liquid ratio of 1:5 – 1:10 and temperature in the range of 20 – 40 °C. The main chlorine-containing phases in the dust are NaCl and KCl, which is confirmed by the transition of Na^+, K^+ and Cl^- ions into solution. The maximum transition of chlorine reaches 98 %, while its content in the dust decreases from 2 % to less than 0.2 %. Significant losses of zinc and other valuable elements were not recorded. The main chlorine-containing phase in the dust under study is NaCl, since the presence of Na in dry residual portions was not detected. The poorly soluble compounds PbOHCl and $Pb_2CO_3Cl_2$ are absent. To a lesser extent, chlorine is in the form of KCl, which is confirmed by the presence of K in the dry residual portion. It should also be noted that calcium actively transfers, which may indicate the presence of calcium hydroxide $Ca(OH)_2$ in the dust. Additionally, the possibility of using waste water for repeated washing was established, which makes the method ecologically and economically feasible. The results obtained confirm the efficiency and practical applicability of the method of preliminary cleaning of EAF dust from chlorine by water washing before subsequent processing.

Keywords: EAF dust, chlorine, zinc, chlorine removal, dechlorination, recycling, water washing

Acknowledgements: The work was supported by the Russian Science Foundation, grant No. 24-79-10120, https://rscf.ru/project/24-79-10120/.

For citation: Grigor'ev E.V., Kapelyushin Yu.E., Ryazanov A.G., Bil'genov A., Stepanov D.V., Khalikulov A.A. Removal of chlorine from electric arc furnace dust by static washing with water. *Izvestiya. Ferrous Metallurgy*. 2026;69(1):14–22.
https://doi.org/10.17073/0368-0797-2026-1-14-22

---

[*] Based on the materials of the 16th International Scientific Conference "Physicochemical Foundations of Metallurgical Processes" named after Academician A.M. Samarin.

Удаление хлора из пыли дугового сталеплавильного производства методом статической промывки водой*

Е. В. Григорьев, Ю. Е. Капелюшин, А. Г. Рязанов,
А. Бильгенов, Д. В. Степанов, А. А. Халикулов

Южно-Уральский государственный университет (Россия, 454080, Челябинск, пр. Ленина, 76)

grigorevev@susu.ru

Аннотация. Пыль электродугового сталеплавильного производства (ЭДП) представляет собой сложный многокомпонентный отход металлургической промышленности, содержащий такие ценные элементы, как железо и цинк. Однако, помимо железа и цинка, пыль ЭДП бывает загрязнена различными примесями, в частности хлором, что затрудняет её последующую переработку. В работе исследовалась возможность удаления хлора из пыли ЭДП методом статической промывки водой. Определены основные параметры: время выдержки, температурный режим, соотношение твердого к жидкому, а также оценена возможность повторного использования отработанной воды. В ходе исследований определены оптимальные параметры процесса промывки пыли водой: время выдержки 1 ч, соотношение твёрдого к жидкому 1:5 – 1:10 и температура в интервале 20 – 40 °С. Показано, что основными хлорсодержащими фазами в пыли являются NaCl и KCl, это подтверждается переходом ионов Na^+, K^+ и Cl^- в раствор. Максимальный переход хлора достигает 98 %, при этом его содержание в пыли снижается с 2 % до менее 0,2 %. Существенные потери цинка и других ценных элементов не зафиксированы. Установлено, что в исследуемой пыли основной хлорсодержащей фазой является NaCl ввиду того, что наличие натрия в сухих остатках не выявлено. Сложнорастворимые соединения PbOHCl и $Pb_2CO_3Cl_2$ отсутствуют. В меньшей степени хлор находится в виде KCl, что подтверждается наличием калия в сухом остатке. Также следует отметить активный переход кальция, что может свидетельствовать о наличии гидроксида кальция $Ca(OH)_2$ в пыли. Дополнительно установлена возможность использования отработанной воды для повторной промывки, что делает метод экологически и экономически целесообразным. Полученные результаты подтверждают эффективность и практическую применимость метода предварительной очистки пыли ЭДП от хлора посредством водной промывки перед последующей переработкой.

Ключевые слова: пыль ЭДП, хлор, цинк, удаление хлора, дехлорирование, переработка, водная промывка

Благодарности: Исследование выполнено за счет гранта Российского научного фонда № 24-79-10120, https://rscf.ru/project/24-79-10120/.

Для цитирования: Григорьев Е.В., Капелюшин Ю.Е., Рязанов А.Г., Бильгенов А., Степанов Д.В., Халикулов А.А. Удаление хлора из пыли дугового сталеплавильного производства методом статической промывки водой. *Известия вузов. Черная металлургия*. 2026;69(1):14–22. https://doi.org/10.17073/0368-0797-2026-1-14-22

* По материалам XVI Международной научной конференции «Физико-химические основы металлургических процессов» имени академика А.М. Самарина.

INTRODUCTION

The processing of metallurgical waste that is suitable for recycling remains a pressing global challenge. One such waste stream is electric arc furnace (EAF) dust, which is generated during steelmaking and captured by gas-cleaning systems. The primary value of EAF dust lies in its content of iron and zinc. Iron concentrations typically range from 20 to 50 %, while zinc contents vary between 2 and 25 % [1 – 3]. It is estimated that more than 30 million tons of EAF dust are currently accumulated in waste dumps at metallurgical plants across the Russian Federation. At present, however, the majority of this material remains unprocessed[1] [4; 5]. The processing of EAF dust is hindered by its complex and heterogeneous morphology, as well as by the presence of contaminating impurities, including lead, fluorine, and chlorine [6 – 8]. During electrolytic zinc production, these impurities cause several technological problems, such as difficulties in removing deposited zinc [9], corrosion of lead-based anodes, and increased electric power consumption. In the case of pyrometallurgical processing, careful control of operating conditions is required, as chlorine can promote the formation of highly toxic organic compounds, including dioxins and furans [10 – 12]. Among the available processing routes, hydrometallurgical processing is one of the main approaches used for EAF dust treatment. Most studies in this area focus on zinc extraction; however, under hydrometallurgical conditions, almost all iron becomes unsuitable for further processing, limiting its subsequent utilization [13; 14].

A number of studies have reported methods for chloride removal from EAF dust, including water washing [15 – 17]. These methods are generally effective provided that poorly soluble compounds such as PbOHCl and $Pb_2CO_3Cl_2$ are absent. In [15], water leaching of chloride ions from EAF dust with an initial chlorine content of 2.14 % was investigated. The authors demonstrated that 99.9 % of chlorides could be removed at a natural pH of 12 and a temperature of 25 °C. As a result, the chlo-

---

[1] World Steel in Figures 2024. Available at URL: https://worldsteel.org/data/world-steel-in-figures-2024/ (Accessed 12.03.2025).

Table 1. **Average composition of EAF dust, wt. %**

Таблица 1. **Средний состав исследуемой пыли ЭДП, мас. %**

Element	O	Na	Mg	Si	S	Cl	K	Ca	Cr	Mn	Fe	Cu	Zn	Pb	Total
Average value	27.0	2.3	0.8	2.2	0.8	1.8	1.7	3.9	0.5	4.5	40.2	0.5	12.9	1.0	100.0

rine content decreased to below 0.02 – 0.04 %, which is close to the detection limit of *X*-ray fluorescence (XRF) analysis.

The experiments were performed using distilled water at a solid-to-liquid ratio of 1:10, with washing times ranging from 5 to 60 min. Changes in the mineral composition of the dust and its behavior during leaching were systematically analyzed. The highest dechlorination rate was observed within the first 5 min, while most chlorides were removed within 40 min. Overall, water washing reduced the total chloride content from 70,200 to 17,500 mg/kg, corresponding to a removal efficiency of 75 %. Temperature was found to have a pronounced effect on the process. At 80 °C, chlorides were removed more rapidly than at room temperature, and the overall removal efficiency increased to 88 %. Nevertheless, the dechlorination efficiency reported in [18] remained lower than that achieved in [15], where values above 99 % were obtained. This discrepancy was attributed to the possible formation of water-insoluble compounds.

The aim of the present study is to investigate the possibility of chlorine removal from EAF dust generated at a major metallurgical enterprise using static washing with water, as well as to assess the feasibility of reusing waste water for repeated washing.

Materials and equipment

Dust obtained from one of the country's major metallurgical enterprises was used in this study. The average chemical composition of the initial dust is summarized in Table 1.

Based on *X*-ray phase analysis and scanning electron microscopy, the predominant chlorine-containing phases in the dust were identified as sodium chloride and potassium chloride (NaCl and KCl). Published data indicate that both compounds are readily soluble in water. The solubility of sodium chloride is 35.6 g/100 mL at 0 °C, 35.9 g/100 mL at 25 °C, and 39.1 g/100 mL at 100 °C, while potassium chloride exhibits solubilities of 28.1 g/100 mL at 0 °C, 34.0 g/100 mL at 25 °C, and 56.7 g/100 mL at 100 °C [19]. Prior to experimentation, the key process parameters requiring optimization were identified, namely washing time, temperature, and solid-to-liquid ratio. Analytical measurements were performed using an OPTIMA 2100 DV inductively coupled plasma optical emission spectrometer (ICP-OES), with an analytical accuracy of 5 – 7 % of the element mass; a JEOL JSM-6460LV scanning electron microscope; an I-160-MI laboratory ion meter; and a chloride-selective ion-selective electrode (ELIS-131Cl).

Experimental procedure

The concentrations of chlorides and other elements were determined in the resulting solutions. The dried solid residues were subsequently examined by scanning electron microscopy. To evaluate the effect of washing time, 50 g portions of the initial dust were placed in separate containers and mixed with 500 mL of water, corresponding to a solid-to-liquid ratio of 1:10. The suspensions were maintained at room temperature for predetermined time intervals. After washing, the liquid phase was decanted, and the solid residue was dried. To investigate the influence of the solid-to-liquid ratio, the samples were washed at room temperature for a fixed washing time of 1 h. The following solid-to-liquid ratios were examined: 1:1, 1:2, 1:5, 1:15, and 1:20. After washing, the solution was decanted and the solid residue was dried. To determine the effect of temperature, a suspension of the initial dust and water was heated in a drying oven to the required temperature. The washing was then carried out in separate flasks at a solid-to-liquid ratio of 1:10 and a washing time of 1 h. After washing, the solution was decanted and the solid residue was dried.

Results

The effects of washing time, temperature, and solid-to-liquid ratio, as well as the results of experiments on the reuse of waste water, are summarized in Tables 2 – 11.

Optimization of washing time

The experiments were performed at 20 °C and a solid-to-liquid ratio of 1:10. A single experiment was carried out for each selected washing time.

For scanning electron microscopy, five spectra were acquired for each sample, with three areas analyzed per spectrum. The average chlorine content in the dry residue, calculated from these measurements, is reported in Table 3.

The results demonstrated that the degree of chlorine transfer from the dust into the solution was essentially independent of washing time over the range investigated.

Table 2. **Chemical analysis of solution after different washing time, mg/L**

Таблица 2. **Химический анализ воды при разном времени выдержки, мг/л**

Washing time, h	Analytical method															
	Inductively coupled plasma optical emission spectrometry															Direct ionometry
	Al	Ca	Co	Cr	Cu	K	Mg	Mn	Na	Ni	P	Pb	Si	Ti	Zn	Cl^-
1	3.4	361.5	0	1.5	0.1	95.96	1.4	0	597	0	2.0	0.3	2.5	0	0.8	2.91
3	1.3	572.8	0	2.5	0.3	107.3	3.9	0	637	0	1.7	1.8	3.3	0	2.1	2.99
6	1.0	407.4	0	2.1	0	105.4	6.1	0	656	0	1.7	0.5	5.8	0	1.2	2.90
12	7.1	477.9	0	2.5	0.3	102.0	6.9	0.4	605	0	7.4	0.3	6.5	0	2.1	3.25
24	0.3	479.5	0	2.1	0	98.76	4.1	0	597	0	0.6	0.8	4.8	0	0.2	2.96
72	0.4	445.6	0	2.7	0	94.48	2.8	0	559	0	0.2	0.3	5.0	0	1.0	3.13

Table 3. **Results of electron microscopy of chlorine content in EAF dust after different washing time, wt. %**

Таблица 3. **Результаты изучения содержания хлора в пыли ЭДП электронной микроскопией при различном времени выдержки, мас. %**

Washing time, h	Spectrum 1	Spectrum 2	Spectrum 3	Spectrum 4	Spectrum 5
1	0.29	0.04	0.20	0.29	0.58
72	0	0.16	0.62	0	0.11

Table 4. **Results of chemical analysis of solution at different ratios of solid:liquid, mg/L**

Таблица 4. **Результаты химического анализа воды при разном соотношении твердое:жидкое, мг/л**

Solid:liquid ratio	Analytical method*									
	Inductively coupled plasma optical emission spectrometry									Direct ionometry
	Al	Ca	Cr	K	Mg	Na	P	Pb	Si	Zn	Cl^-
1:1	0.69	893.3	9.60	500.0	1.03	500.00	0.22	0.12	5.79	2.20	24.70
1:2	0.26	1083.0	3.61	455.9	3.59	500.00	0.13	0.09	4.86	1.52	12.10
1:5	0.23	678.7	2.41	243.6	2.09	500.00	0.10	0.02	3.57	0.10	6.42
1:15	0.07	299.4	0.93	70.7	1.71	446.62	0.06	0.01	2.70	0	2.36
1:20	0.14	241.9	0.70	52.5	2.00	326.92	0.17	0.21	2.90	0	1.77

* Cu, Ti, Ni, Co, Fe, and Mn were not detected.

Table 5. **Results of electron microscopy of EAF dust at different ratios solid:liquid, wt. %**

Таблица 5. **Результаты электронной микроскопии пыли при разном соотношении твердое:жидкое, мас. %**

Solid:liquid ratio	Element													Total
	O	Mg	Al	Si	S	Cl	K	Ca	Cr	Mn	Fe	Cu	Zn	
1:1	17.31	1.18	0.62	3.06	0.33	0.32	0.56	4.29	0.73	5.23	50.77	0.84	14.77	100.00
1:2	15.28	1.12	0.36	2.63	0.40	0.31	0.56	4.29	0.54	5.60	52.00	0.75	16.16	100.00
1:5	16.65	1.32	0.38	2.64	0.26	0.45	0.40	4.69	0.74	5.55	50.95	0.48	15.64	100.00
1:15	15.59	1.21	0.38	2.86	0.25	0.19	0.47	4.04	0.70	5.47	52.79	0.46	15.59	100.00
1:20	17.21	1.45	0.20	2.89	0.13	0.18	0.27	4.45	0.84	5.26	50.77	0.85	15.52	100.00

Table 6. **Results of chemical analysis of solution at different temperatures, mg/L**

Таблица 6. **Результаты химического анализа воды при разной температуре, мг/л**

Temperature, °C	Analytical method*											
	Inductively coupled plasma optical emission spectrometry											Direct ionometry
	Al	Ca	Cr	Cu	K	Mg	Na	P	Ti	Si	Zn	Cl^-
40	0.16	463.38	1.34	0.50	100.48	9.66	706.77	0.06	0.29	3.05	0.51	3.16
60	1.17	438.08	1.67	0.23	103.37	2.78	649.62	0.11	0.22	254.00	0.52	3.19
80	0.13	302.66	1.22	0.01	90.84	2.21	544.09	0.08	0.25	2.97	0.75	2.84
* Ni, Co, Fe, Mn, and Pb were not detected.												

Table 7. **Results of electron microscopy of EAF dust at different temperatures, wt. %**

Таблица 7. **Результаты электронной микроскопии пыли ЭДП при разной температуре мас. %**

Temperature, °C	Element													Total
	O	Mg	Al	Si	Cl	K	Ca	Cr	Mn	Fe	Cu	Zn	Pb	
40	18.25	1.15	0.52	3.08	0.19	0.52	4.10	0.43	5.39	49.69	0.59	15.22	0.94	100.00
60	17.57	1.04	0.69	2.79	0.19	0.25	4.42	0.70	5.34	50.87	0.80	14.61	0.97	100.00
90	17.55	1.41	0.38	3.31	0.11	0.62	4.44	0.51	5.40	50.79	0.47	14.02	1.16	100.00

Table 8. **Results of chemical analysis of water after repeated washing with waste water “P2”. mg/L**

Таблица 8. **Результаты химического анализа воды при повторной промывке водой «П2». мг/л**

Washing stage	Analytical method*											
	Inductively coupled plasma optical emission spectrometry											Direct ionometry
	Al	Ca	Cr	Cu	K	Mg	Mn	Na	Pb	Si	Zn	Cl^-
After the first washing	1.4	427.95	2.5	1.9	112.2	0.6	0.2	500	0.1	2.2	12.2	3.70
P2 (sample *1*)	4.3	926.30	3.7	1.5	270.1	4.2	0.6	500	0.1	6.4	10.5	6.37
P2 (sample *2*)	0.2	940.52	3.9	0	264.0	2.4	0	500	0	2.0	0.34	6.25
P2 (sample *3*)	0.2	1014.4	4.0	0.3	283.1	2.2	0	500	0.1	2.1	0.44	6.24
* Ti, Ni, Co, Fe, and P were not detected.												

Table 9. **Results of electron microscopy of solid dust residual portion after repeated washing with waste water “P2”. wt. %**

Таблица 9. **Результаты электронной микроскопии твёрдого остатка пыли после повторной промывки «П2». мас. %**

Washing stage	Element													Total
	O	Mg	Al	Si	S	Cl	K	Ca	Cr	Mn	Fe	Cu	Zn	
P2 (*1*)	16.63	1.18	0.40	3.16	0.37	0.25	0.48	4.56	0.73	5.62	52.00	0.73	13.88	100.00
P2 (*2*)	17.09	0.94	0.49	3.32	0.19	0.19	0.62	4.34	0.74	5.38	55.53	0.74	13.61	100.00
P2 (*3*)	16.29	1.71	0.77	3.19	0.34	0.18	0.41	4.12	0.79	5.28	52.69	0.74	13.86	100.00

Table 10. **Results of chemical analysis of solution after additional repeated washing with waste water "P3". mg/L**

Таблица 10. **Результаты химического анализа воды после повторной промывки «П3». мг/л**

Washing stage	Analytical method*												
	Inductively coupled plasma optical emission spectrometry												Direct ionometry
	Al	Ca	Cr	Cu	K	Mg	Mn	Na	P	Pb	Si	Zn	Cl^-
Combined solution after P2	0.21	484.66	2.33	0.01	190.75	2.78	0	500	0.10	0	0.73	0.33	5.05
P3 (sample *1*)	0.35	754.29	3.14	0.11	316.06	6.32	0.01	500	0.07	0	1.32	0.56	7.20
P3 (sample *2*)	0.23	781.73	3.17	0.01	315.30	6.12	0.01	500	0.08	0.05	0.14	0.62	6.88
P3 (sample *3*)	0.53	807.38	3.03	0.29	318.48	7.92	0.02	500	0.30	0.06	0.13	0.75	6.59

* Ti, Ni, Co, Fe, and P were not detected. For Na, the reported values correspond to the upper limit of the analytical method (≫500 mg/L).

Table 11. **Results of electron microscopy of EAF dust after repeated washing with waste water "P3". wt. %**

Таблица 11. **Результаты электронной микроскопии пыли после повторной промывки «П3». мас. %**

Washing stage	Element													Total
	O	Mg	Al	Si	Cl	K	Ca	Cr	Mn	Fe	Cu	Zn	Pb	
P3 (*1*)	17.85	1.14	0.52	3.09	0.16	0.38	4.18	0.63	5.58	50.40	0.60	14.34	1.11	100.00
P3 (*2*)	17.33	1.53	0.41	2.96	0.15	0.49	4.41	0.56	5.58	50.87	0.57	14.45	0.69	100.00
P3 (*3*)	17.43	1.17	0.43	3.32	0.19	0.48	4.50	0.75	5.48	49.78	0.51	14.77	1.20	100.00

Comparable chlorine removal was observed at both the shortest and longest washing durations. On this basis, the minimum washing time of 1 h was adopted for all subsequent experiments. In addition to chlorine, potassium, sodium, and calcium exhibited substantial transfer into the solution. The concurrent transfer of potassium and sodium indicates that chlorine in the dust is present predominantly in the form of NaCl and KCl. The pronounced transfer of calcium may, in turn, indicate the presence of calcium hydroxide ($Ca(OH)_2$) in the dust.

Effect of the solid-to-liquid ratio

The experiments were conducted at a temperature of 20 °C and a washing time of 1 h. One experiment was performed for each selected solid-to-liquid ratio. The results showed that the optimal solid-to-liquid ratios were 1:5 and 1:10, owing to ease of filtration and high reliability of the results. At a ratio of 1:1, the suspension was excessively dense, and dust losses reached up to 30 %. In addition, the large volume of material subjected to filtration led to filter rupture, requiring the use of three containers with two filters each. At a ratio of 1:2, the suspension viscosity decreased; however, dust losses remained high (up to 15 %), and filter rupture was still observed. In this case, two containers with one filter each were used. At a ratio of 1:5, the suspension was sufficiently fluid, and dust losses decreased to approximately 8 %. Filtration proceeded uniformly and did not require additional containers. At ratios of 1:15 and higher, no dust losses were observed; however, these conditions resulted in excessive water consumption, rendering such ratios impractical.

The average values obtained from three different measurement points are presented in Table 5. As follows from the experimental data, similar transfer behavior of the investigated elements was observed across the different solid-to-liquid ratios. Based on these considerations, all subsequent experiments were carried out at a solid-to-liquid ratio of 1:10, due to its operational convenience.

Static experiments on the effect of temperature

The static experiments were carried out at a washing time of 1 h and a solid-to-liquid ratio of 1:10. One experiment was performed at each selected temperature.

The results obtained at different temperatures showed that chlorine transfer was complete regardless of temperature, while the contents of the other elements remained essentially unchanged.

Experiments on reuse of waste water

To assess the feasibility of dechlorination of EAF dust using previously used washing water, the possibility of multiple reuse of the washing water was investigated. During these experiments, a white flocculent precipitate was observed on the surface of the used water and on the walls of the containers. The chemical composition of this precipitate was not determined at this stage, as it was not possible to collect a sufficient amount for analysis. Prior to repeated washing, the water was filtered to remove the precipitate. The washing was then conducted at a solid-to-liquid ratio of 1:10 and a washing time of 1 h, without heating; all experiments were performed at room temperature. For convenience, the repeated washing experiments were designated as "P2" and "P3". Thus, different EAF dust samples were washed three times using the same water.

To assess reproducibility, several identical 50 g samples of EAF dust were repeatedly washed using waste water.

The results of the repeated washing experiments showed that chlorine continued to transfer into the water, although inconsistent trends were observed for some of the other elements. The water samples P2 (*1*), P2 (*2*), and P2 (*3*) were then combined, and this same water was used for a third washing of three new 50 g dust samples. The corresponding results are presented in Table 10.

Following the third washing with the same water, it can be concluded that chlorine continues to transfer into the reused water, even after two prior washing cycles.

Discussion

In all experiments involving static washing of EAF dust with water, a minor mass loss of approximately 3 – 5 g was observed. This loss can be attributed to the high dispersity of the dust and to material losses resulting from adhesion of fine particles to the walls of the glass vessels.

An identical degree of chlorine transfer from EAF dust into the solution was observed at both the minimum and maximum washing times investigated. Consequently, a washing time of 1 h was adopted for all subsequent experiments. In addition to chlorine, K^+, Na^+, and Ca^{2+} were found to transfer actively into the solution, as evidenced by the data presented in Tables 2, 3, and 5. The transfer of potassium and sodium indicates that chlorine in the dust is present predominantly in the form of NaCl and KCl. The pronounced transfer of calcium, in turn, may indicate the presence of calcium hydroxide, $Ca(OH)_2$, in the dust.

The experiments also showed that the optimal solid-to-liquid ratios fall within the range of 1:5 to 1:10, which provides both operational convenience and the highest reliability of the results.

The average values obtained from three different measurement points are presented in Tables 4 and 5. As follows from the experimental data, similar transfer behavior of the investigated elements was observed across the different solid-to-liquid ratios.

The experiments performed at different temperatures demonstrated that chlorine transfer occurs completely regardless of temperature, while the contents of the other elements remain essentially unchanged. At the same time, it should be noted that higher temperatures promote increased dissolution of heavy metals into the solution and lead to an acceleration of the reaction kinetics.

After repeated washing, it was established that chlorine continues to transfer into the water, and the degree of dechlorination of new EAF dust samples was approximately 86 %, while no zinc losses were detected. The results of the repeated washing experiments are presented in Tables 8 – 11. In the solution obtained after the first use of water for washing, the chloride ion concentration was 3.7 mg/L. After the second use of the same water (experiments P2), the average chloride ion concentration increased to 6.5 mg/L. Following the third use of the same water (experiments P3), the chloride ion concentration reached 7.2 mg/L. At the same time, the chlorine content in each EAF dust sample washed with the same water did not exceed 0.2 wt. %.

Conclusions

Water washing can therefore be considered a highly effective method for dechlorination of EAF dust, provided that poorly soluble compounds such as PbOHCl and $Pb_2CO_3Cl_2$ are absent. The static experiments made it possible to establish the following parameters for laboratory conditions: an optimal washing time of 1 h to transfer chlorine into the aqueous phase and a solid-to-liquid ratio in the range of 1:5 – 1:10. It was also established that, in the material under study, the dominant chlorine-containing phase is NaCl, as indicated by electron microscopy data (Tables 3 and 4) and by the absence of sodium in the dry residues. To a lesser extent, chlorine is present in the form of KCl, which is confirmed by the presence of potassium in the dry residue. The high transfer of calcium into solution suggests that calcium is partially present in the form of $Ca(OH)_2$, which is readily soluble in water. The experiments demonstrated the feasibility of multiple reuse of the same waste water for washing EAF dust to remove chlorine. Under the conditions investigated, complete saturation of the solution with chlorine was not achieved.

In all experiments, a stable transfer of chloride ions into the aqueous phase was observed, with the degree of chlorine transfer reaching up to 98 %. As a result of static water washing, the chlorine content in the initial dust decreased from approximately 2 to 0.2 wt. %.

References / Список литературы

1. Roshchin V.E., Roshchin A.V. Electrometallurgy and Steel Metallurgy: Textbook. Chelyabinsk: SUSU; 2013:572. (In Russ.).

Рощин В.Е., Рощин А.В. Электрометаллургия и металлургия стали: Учебник. Челябинск: Издательский центр ЮУрГУ; 2013:572.

2. Snurnikov A.A. Zinc Hydrometallurgy:

Снурников А.А. Гидрометаллургия цинка: Учебник. Москва: Металлургия; 1981:384.

3. Zaitsev V.Ya. Metallurgy of Lead and Zinc. Moscow: Metallurgiya; 1985:262. (In Russ.).

Зайцев В.Я. Металлургия свинца и цинка. Москва: Металлургия; 1985:262.

4. Toporkova Yu.I., Bludova D., Mamyachenkov S.V., Anisimova O.S. A review of processing methods for electric arc furnace dust. *iPolytech Journal*. 2021;25(5):643–680. (In Russ.). https://doi.org/10.21285/1814-3520-2021-5-643-680

Топоркова Ю.И., Блудова Д., Мамяченков С.В., Анисимова О.С. Обзор методов переработки пылей электродуговой плавки. *iPolytech Journal*. 2021;25(5):643–680. https://doi.org/10.21285/1814-3520-2021-5-643-680

5. Kozlov P.A. Waelz Process. Moscow: Ruda i metally; 2002:173. (In Russ.).

Козлов П.А. Вельц-процесс. Москва: ИД «Руда и металлы»; 2002:173.

6. Ryazanov A.G., Mikhailov G.G., Senin A.V., Sokorov D.I. Efficiency of chloride removal from zinc-containing products depending on the parameters of calcination by microwave electromagnetic field. *Bulletin of South Ural State University. Metallurgy*. 2021;21(2):18–29. (In Russ.).

Рязанов А.Г., Михайлов Г.Г., Сенин А.В., Сокоров Д.И. Эффективность удаления хлоридов из цинксодержащих продуктов в зависимости от параметров прокаливания электромагнитным полем СВЧ. *Вестник Южно-Уральского государственного университета. Металлургия*. 2021;21(2):18–29.

7. Chmielarz A., Gnot W. Conversion of zinc chloride to zinc sulphate by electrodialysis – a new concept for solving the chloride ion problem in zinc hydrometallurgy. *Hydrometallurgy*. 2001;61(1):21–43. https://doi.org/10.1016/S0304-386X(01)00153-0

8. Li C.L., Tsai M.S. A crystal phase study of zinc hydroxide chloride in electric-arc-furnace dust. *Journal of Materials Science*. 1993;28:4562–4570. https://doi.org/10.1007/BF00414243

9. Adhia J.D. Effect and control of impurities in electrolytic zinc production. In: *Symposium on Non-Ferrous Metals Technology. Vol. III: Nickel, Lead, Zinc, Rare earth and Nuclear Metals. NML, Jamshedpur*; 1969:1–10.

10. Simonyan L.M., Demidova N.V. Dioxins and furans in zinc-containing metallurgical dust: behavior and formation processes. *Izvestiya. Ferrous Metallurgy*. 2019;62(7):557–563. (In Russ.). https://doi.org/10.17073/0368-0797-2019-7-557-563

Симонян Л.М., Демидова Н.В. Диоксины и фураны в цинксодержащей металлургической пыли: процессы формирования и поведение. *Известия вузов. Черная металлургия*. 2019;62(7):557–563. https://doi.org/10.17073/0368-0797-2019-7-557-563

11. Simonyan L.M., Demidova N.V. Dioxins and furans' behavior in the process of zinc and lead removing from EAF dust. *Izvestiya. Ferrous Metallurgy*. 2019;62(11):840–845. (In Russ.). https://doi.org/10.17073/0368-0797-2019-11-840-845

Симонян Л.М., Демидова Н.В. Изучение поведения диоксинов и фуранов в процессе удаления цинка и свинца из пыли ДСП. *Известия вузов. Черная металлургия*. 2019;62(11):840–845. https://doi.org/10.17073/0368-0797-2019-11-840-845

12. Stanmore B.R. The formation of dioxins in combustion systems. *Combustion and Flame*. 2004;136(3):398–427. https://doi.org/10.1016/j.combustflame.2003.11.004

13. Yoo J.G., Kim G.S., Jo Y.M. Separation of chlorides from EAF dust. *Journal of Industrial and Engineering Chemistry*. 2004;10:894–898.

14. Iliev P., Stefanova V., Lucheva B., Kolev D. Purification of zinc containing Waelz oxides from chlorine and fluorine. *Journal of Chemical Technology and Metallurgy*. 2017;52(2):252–257.

15. Bruckard W.J., Davey K.J., Rodopoulos T., Woodcock J.T., Italiano J. Water leaching and magnetic separation for decreasing the chloride level and upgrading the zinc content of EAF steelmaking baghouse dusts. *International Journal of Mineral Processing*. 2005;75(1-2):1–20. https://doi.org/10.1016/j.minpro.2004.04.007

16. Wang Q., Yang J., Wang Q., Wu T. Effects of water-washing pretreatment on bioleaching of heavy metals from municipal solid waste incinerator fly ash. *Journal of Hazardous Materials*. 2009;162(2–3):812–818. https://doi.org/10.1016/j.jhazmat.2008.05.125

17. Bludova D.I., Mamyachenkov S.V., Anisimova O.S. Methods for removing chloride ions to manufacture zinc from arc melting dust. *iPolytech Journal*. 2023;27(2):392–421. (In Russ.). https://doi.org/10.21285/1814-3520-2023-2-392-421

Блудова Д.И., Мамяченков С.В., Анисимова О.С. Методы удаления хлорид-ионов при производстве цинка из пыли электродуговой плавки. *iPolytech Journal*. 2023; 27(2):392–421. https://doi.org/10.21285/1814-3520-2023-2-392-421

18. Chen W.-S., Shen Y.-H., Tsai M.-S., Chang F.-C. Removal of chloride from electric arc furnace dust. *Journal of Hazardous Materials*. 2011;190(1–3):639–644. https://doi.org/10.1016/j.jhazmat.2011.03.096

19. Nekrasov B.V. Fundamentals of General Chemistry: Vol. 1. Moscow: Khimiya; 1973:656. (In Russ.).

Некрасов Б.В. Основы общей химии: Т. 1. Москва: Химия, 1973:656.

Information about the Authors

Evgenii V. Grigor'ev*, Research Engineer of the Research Laboratory "Hydrogen Technologies in Metallurgy"*, South Ural State University
E-mail: grigorevev@susu.ru

Yurii E. Kapelyushin*, Senior Researcher of the Research Laboratory "Hydrogen Technologies in Metallurgy"*, South Ural State University
ORCID: 0000-0002-3352-1780
E-mail: kapelyshnye@susu.ru

Andrei G. Ryazanov*, Cand. Sci. (Eng.), Senior Lecturer of the Chair of Materials Science and Physical Chemistry of Materials*, South Ural State University
ORCID: 0000-0002-3727-8757
E-mail: riazanovag@susu.ru

Arman Bil'genov*, Senior Lecturer of the Chair "Pyrometallurgical and Foundry Technologies"*, South Ural State University
ORCID: 0009-0001-8592-7870
E-mail: bilgenova@susu.ru

Dmitrii V. Stepanov*, Research Engineer of Department of Scientific and Innovation Activities*, South Ural State University
E-mail: aqaseq@gmail.com

Artur A. Khalikulov*, Laboratory Assistant of Department of Scientific and Innovation Activities*, South Ural State University
E-mail: artur.dragonil@mail.ru

Сведения об авторах

Евгений Вячеславович Григорьев*, инженер-исследователь научно-исследовательской лаборатории «Водородные технологии в металлургии»*, Южно-Уральский государственный университет
E-mail: grigorevev@susu.ru

Юрий Евгеньевич Капелюшин*, старший научный сотрудник научно-исследовательской лаборатории «Водородные технологии в металлургии»*, Южно-Уральский государственный университет
ORCID: 0000-0002-3352-1780
E-mail: kapelyshnye@susu.ru

Андрей Геннадьевич Рязанов*, к.т.н., старший преподаватель кафедры «Материаловедение и физико-химия материалов»*, Южно-Уральский государственный университет
ORCID: 0000-0002-3727-8757
E-mail: riazanovag@susu.ru

Арман Бильгенов*, старший преподаватель кафедры «Пирометаллургические и литейные технологии»*, Южно-Уральский государственный университет
ORCID: 0009-0001-8592-7870
E-mail: bilgenova@susu.ru

Дмитрий Владимирович Степанов*, инженер-исследователь управления научной и инновационной деятельности*, Южно-Уральский государственный университет
E-mail: aqaseq@gmail.com

Артур Алексеевич Халикулов*, лаборант управления научной и инновационной деятельности*, Южно-Уральский государственный университет
E-mail: artur.dragonil@mail.ru

Contribution of the Authors

E. V. Grigor'ev – conducting the research, data processing, writing the text.
Yu. E. Kapelyushin – scientific guidance, writing and editing the text.

A. G. Ryazanov – conducting the experiments, writing the text.

A. Bil'genov – editing the text, analysis of literary data.

D. V. Stepanov – conducting the experiments, writing the text, preparing a literary review.
A. A. Khalikulov – conducting the experiments.

Вклад авторов

Е. В. Григорьев – проведение исследований, обработка данных, написание статьи.
Ю. Е. Капелюшин – руководство, написание статьи, редактирование статьи.
А. Г. Рязанов – постановка экспериментов, участие в написании статьи.
А. Бильгенов – редактирование статьи, анализ литературных данных.
Д. В. Степанов – проведение экспериментов, написание статьи, подготовка литературного обзора.
А. А. Халикулов – проведение экспериментов.

Received 20.05.2025
Revised 02.07.2025
Accepted 28.08.2025

Поступила в редакцию 20.05.2025
После доработки 02.07.2025
Принята к публикации 28.08.2025