

RESEARCH

Open Access



# Extraction of arsenic from fine dust of copper smelters by reduction roasting with natural gas

Nurlan Dosmukhamedov<sup>1</sup>, Abdilmalik Takishov<sup>2</sup>, Erzhan Zholdasbay<sup>2</sup> and Aidar Argyn<sup>2\*</sup>

## Abstract

One of the current trends in the complex processing of fine dust from copper smelters is their direct leaching with sulfuric acid. As practical results show, high reliable technological parameters are not achieved due to the high content of arsenic in dust. During sulfuric acid leaching of dust, arsenic is distributed between the lead cake and the solution at a ratio of 40 and 60%, respectively. The redistribution of arsenic between leaching products significantly reduces the technological performance and leads to the accumulation of arsenic in the technological scheme. The paper presents the results of comprehensive studies of the elemental and phase composition of fine dust from one of the copper smelters in Kazakhstan. In the initial dust, along with the main phases presented in the form of lead and zinc sulfate, the following typical components were found: oxides of copper, lead, zinc and copper and zinc ferrites. Arsenic is found in two forms—As(III) and As(V). The laboratory installation and technique for conducting reduction roasting of dust with natural gas are presented. The influence of roasting duration, temperature and natural gas consumption on the extraction of arsenic from dust was studied. It has been established that almost complete, up to 99%, extraction of arsenic from dust is achieved with optimal technological roasting parameters: duration  $\tau = 40$  min.; natural gas consumption is 1.5 times higher than the stoichiometrically required amount for the reduction of  $As_2O_5$ , and temperature 500 °C.

**Keywords** Fine dust, Arsenic, Reduction roasting, Natural gas, Duration, Temperature, Extraction, Sublimation

## 1 Introduction

An important task of development of non-ferrous metallurgy of Kazakhstan is organization of new productions aimed at complex processing of substandard semi-products and recycled materials with maximum extraction of valuable metals.

Industrial development of technologies of processing of multi-component arsenic-containing dust of copper and

lead production is among the most important priorities of innovative development of mining and metallurgical industry of Kazakhstan. An important prerequisite for organization of separate production for processing of lead dusts of Kazakhmys and Kazzinc is their multi-component nature, in %: 35–50 Pb; 5–7 Cu; 6–9 Zn; 4–6 Fe; 8–13 As; among others [1].

The increase in the content of toxic and carcinogenic arsenic [2–4] in sulfide primary raw materials significantly affected its distribution between the gas, slag and matte phases in smelting processes towards deterioration [5–7]. Substandard intermediate products, recycled materials and technogenic waste with a high arsenic content obtained in practice have increased their negative impact on the environment

\*Correspondence:

Aidar Argyn  
aidarargyn@gmail.com

<sup>1</sup> Department of Metallurgy and Mineral Processing, Satbayev University, Almaty 050000, Kazakhstan

<sup>2</sup> Department of Mining, Metallurgy and Natural Sciences, Zhezkazgan University Named After O.A. Baikunurov, Zhezkazgan 100600, Kazakhstan



© The Author(s) 2024. **Open Access** This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

and public health. The increased arsenic content significantly challenges their further processing. Arsenic emissions, especially  $\text{As}_2\text{O}_3$ , cause serious environmental pollution and harm to human health. Arsenic control has become one of the important issues for all copper and lead smelters [3, 7].

Materials characterized by a complex chemical composition and containing significant amounts of arsenic include dusts obtained during various copper and lead smelting processes. The chemical composition of the dust depends mainly on the design and technological conditions of the furnace, the type of concentrate and the chemical composition of the concentrate. Even a slight change in operating conditions and the chemical composition of the concentrate can lead to a change in the composition of the dust [8–14]. Dusts from non-ferrous metallurgy are characterized by significant heterogeneity of granulometric, chemical and mineralogical composition [15–17].

In lead production, most of the dust is recycled material and is returned to the initial feed. This makes it possible to concentrate rare (Se, In, Ta, Tl, Cd, etc.) and heavy non-ferrous metals (Zn, Cu, Pb) in recycled dust and simultaneously extract from them. Only a small part of dust with a high content of arsenic and other harmful impurities is removed from circulation and processed separately.

Unlike lead production dust, fine dust from copper smelters is not recyclable and requires separate processing. Particular relevance of this issue is the large volumes of fine dust obtained during the converting of copper matte, both at lead and copper smelters in this region. If previously the problem of processing lead dust from copper smelters was solved by transferring it to lead plants, now this poses a certain problem for copper smelters. Due to the high arsenic content in them, lead factories refuse to accept them for processing. Today, fine dust does not find proper sales and accumulates on the territory of industrial plants.

For the economy of Kazakhstan, the most important task is the transition of the activities of the mining and metallurgical complex of the Republic of Kazakhstan to a circular economy within the framework of the Zero concept waste using resource-saving and energy-efficient technologies. At the same time, the effective functioning of a production management system within a closed cycle must rely on the so-called “principle of three R”—Reduce, Reuse and Recycle. Such a management system of production, which meets the principles of a circular economy, is already widely used in many developed countries [18].

From this perspective the task of developing new technologies aimed at the comprehensive processing of

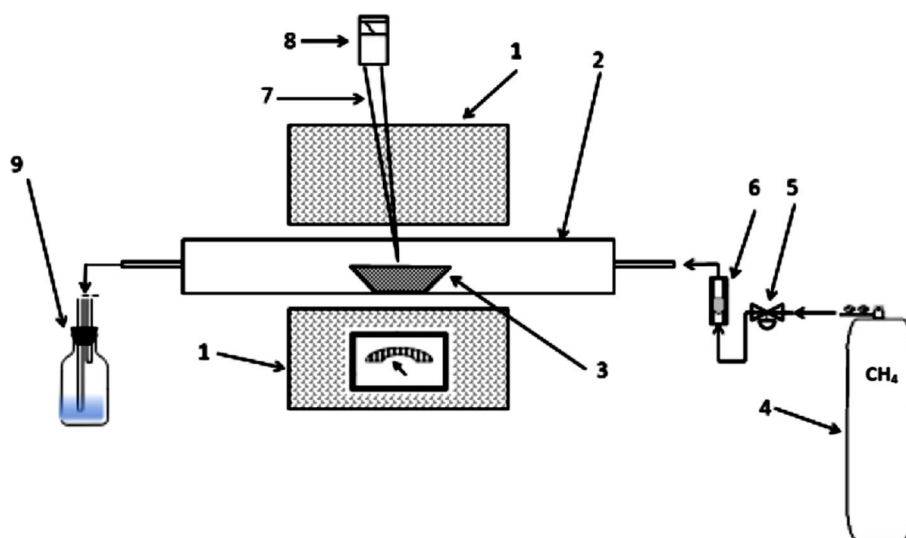
multi-component raw materials—intermediate products, industrial waste, including dust from copper and lead production, seems very relevant.

An important prerequisite for organizing a separate production for processing fine dust from copper smelting production is their multicomponent nature, in %: 35–50 Pb; 5–7 Cu; 6–9 Zn; 4–6 Fe; 8–13 As; among others. The value of dust is enhanced by the presence of dual-use metals in them: rhenium, osmium, selenium, etc. The increase in arsenic content (up to 13%) in the dust of copper smelters in Kazakhstan slows down the development of new highly efficient technologies for their processing.

There are many works in the scientific literature devoted to solving the issue of separate processing of fine dust by pyro- [19–21], hydro-metallurgical and combined methods [22–24]. Each approach of solving a given problem is distinguished by its originality and is applicable to a specific type and composition of the dust being processed. Extensive theoretical and practical material has been accumulated, which has an interest in terms of extracting the main heavy non-ferrous metals—copper, lead and zinc from dust. However, none of the known studies has systematically studied the behavior of arsenic and assessed its impact on the technological performance of the used processes. Only fragmentary points are touched upon regarding the removal of arsenic from the technological scheme and its disposal from solutions obtained after leaching using known methods. When organizing technologies, the authors practically do not consider the observed redistribution of arsenic between products in a negative direction. For example, during direct leaching of dust with sulfuric acid due to the distribution of arsenic between the lead cake (40%) and the solution (60%), a significant accumulation of arsenic occurs in the technological scheme. With further reduction smelting of lead cake, the formation of secondary recycled dust with an increased content of arsenic leads to its accumulation in the overall technological scheme and a significant decrease in the technological, economic and environmental indicators of the technology as a whole.

An effective approach seems to involve preliminary removal of arsenic from dust, and only after that, subjecting it to further leaching with sulfuric acid, as shown in [25] using low-temperature dust roasting (calcination) and subsequent acid leaching.

The purpose of this work is to study the extraction of arsenic from fine dust of a copper smelter by reduction roasting with natural gas. Creating a reduction atmosphere during roasting, on the one hand, eliminates the possibility of oxidation of highly volatile  $\text{As}_2\text{O}_3$  to stable, non-volatile oxide  $\text{As}_2\text{O}_5$ , and on the other hand,



**Fig. 1** Layout of a laboratory installation for dust roasting: 1 – electric furnace Nabertherm 50/250/12 with temperature-controlled controller B410; 2 – quartz reactor; 3 – alumina boat crucible with a sample; 4 – cylinder with  $\text{CH}_4$ ; 5 – valve; 6 – rotameter RM-GS 004 KL4; 7 – thermocouple PP-1; 8 – secondary device KSP-4; 9 – vessel for absorbing gases

ensures maximum reduction of pentavalent arsenic present in dust to  $\text{As}_2\text{O}_3$  with further sublimation from cinder.

To achieve this goal, this work studied the influence of temperature, roasting duration and natural gas consumption on the completeness of arsenic extraction into sublimes in the form of  $\text{As}_2\text{O}_3$  under the conditions of reduction roasting of fine dust of a copper smelter.

## 2 Materials and methods

### 2.1 Materials and experimental procedures

The object of study was fine dust from a copper smelter located in Kazakhstan, obtained after converting autogenous smelting copper mattes in Vanyukov furnaces. Roasting was carried out using natural gas with the composition, vol%: 92.6  $\text{CH}_4$ ; 4.1  $\text{C}_2\text{H}_6$ ; and 1.0  $\text{C}_3\text{H}_8$ . The main experimental equipment used to conduct experiments on the reduction roasting of dust with natural gas is a horizontal electric furnace Nabertherm 50/250/12 with a temperature-controlled controller B410.

Alumina boat crucibles measuring  $120 \times 60 \times 20$  mm were used as containers for loading the initial dust. The layout of the experimental setup for carrying out the reduction roasting of dust with natural gas is shown in Fig. 1.

The order of the experiments was as follows. The boat crucible with a sample of dust of 100 g (3) was loaded into the furnace (1) and heating began to the required

temperature at a rate of  $10^\circ\text{C min}^{-1}$  in a stream of natural gas supplied from a cylinder (4). During the experiments, additional temperature control was carried out with a PP-1 thermocouple (7) and a secondary device KSP-4 (8). The gas flow rate was  $100\text{ mL min}^{-1}$  and was controlled using a RM-GS 004 KL4 rotameter (6). The specified gas flow rate was chosen at the rate of 1.5 times greater than the stoichiometrically required amount for the reduction of arsenic contained in the original dust. As the results of the experiments showed, this gas consumption is quite sufficient to complete reduction of  $\text{As}_2\text{O}_5$  and copper and zinc ferrites present in the dust. The experiments were carried out in a reducing atmosphere. Natural gas was supplied from the moment the furnace was turned on and did not stop until the end of the experiment, which provided reducing conditions for the experiments.

The exhaust gases from the furnace were discharged into a special absorption vessel (9) with a solution of  $\text{Ca}(\text{OH})_2$ . Once the set temperature was reached, the furnace was kept for the required duration and turned off. Once the furnace was cooled down, the boat crucible with its contents was removed. The obtained cinder was weighed and subjected to elemental and phase analysis.

### 2.2 Research methods

Bruker D8 Advance X-ray diffractometer was used to determine the elemental and phase composition of the initial dust and roasting products with  $\alpha\text{-Cu}$  radiation, tube voltage 40 kV, current 40 mA. Processing of the

**Table 1** Chemical composition of fine dust from a copper smelter

Elements	Cu	Pb	Zn	Fe	As	Si	S	O	Others
Content, %	3.04	25.06	5.91	1.35	13.0	0.3	8.19	22.25	20.23

obtained diffraction pattern data and calculation of inter-planar distances was carried out using EVA software. Sample interpretation and phase search were carried out using the Search/match program using the PDF-2 Powder Diffractometric Database. The micromorphology of the materials was characterized by the results of Scanning Electron Microscopes-Energy-dispersive X-Ray Spectroscopy (SEM-EDS) analysis obtained using a JED-2300 EDS (JEOL).

The conducted studies examined the effect of roasting duration (20, 40, 60 min) on the extraction of arsenic from fine dust at a constant temperature of 500 °C. Each experiment was carried out 3 times. The average value of the values obtained in each experiment was taken as the final result.

The main research objective is to remove as much arsenic as possible into sublimates in the form of its volatile compound  $As_2O_3$ .

Due to the complexity of organizing the capture of arsenic-containing sublimates, the extraction of arsenic from the source material into sublimates is controlled considering the quantitative ratios of the initial sample and the solid product (cinder) obtained after the experiment. Before conducting the experiments, the empty boat crucible and the crucible along with the original sample were weighed. After the experiment, the boat crucible with the sample was also weighed. Based on the difference in the amount of the initial sample and the resulting cinder, the amount of sublimates obtained as a result of the experiment was identified. According to the obtained data arsenic recovery ( $\epsilon_{As}$ ) into sublimates was calculated by the formula:

$$\epsilon_{As} = \frac{(g_1 \times m_1) - (g_2 \times m_2)}{(g_1 \times m_1)}$$

where:  $\epsilon_{As}$  – extraction of arsenic into sublimates, %;  
 $g_1$ —the mass fraction of arsenic in the original dust,  
 $m_1$  – amount of initial dust, g;  
 $g_2$ —the mass fraction of arsenic in the cinder;  
 $m_2$  – amount of cinder, g.

To better understand the mechanism of the process of reduction roasting of dust, a detailed thermodynamic analysis of the reactions of interaction of dust components with natural gas was carried out. Thermodynamic calculations were carried out using Chemistry 8.1.5, Outotec HSC software.

### 3 Results and discussion

#### 3.1 Study of the material composition of dust

The elemental and phase compositions of the original dust are given in Table 1 and Fig. 2.

As can be seen in Fig. 2, the main components in dust are lead ( $PbSO_4$ ) and zinc ( $ZnSO_4$ ) sulfates. Due to the low content of other components in the dust, they are not visible on the X-ray diffraction patterns. Dusts have a complex composition, so during research it is necessary to consider the presence of accompanying elements in them.

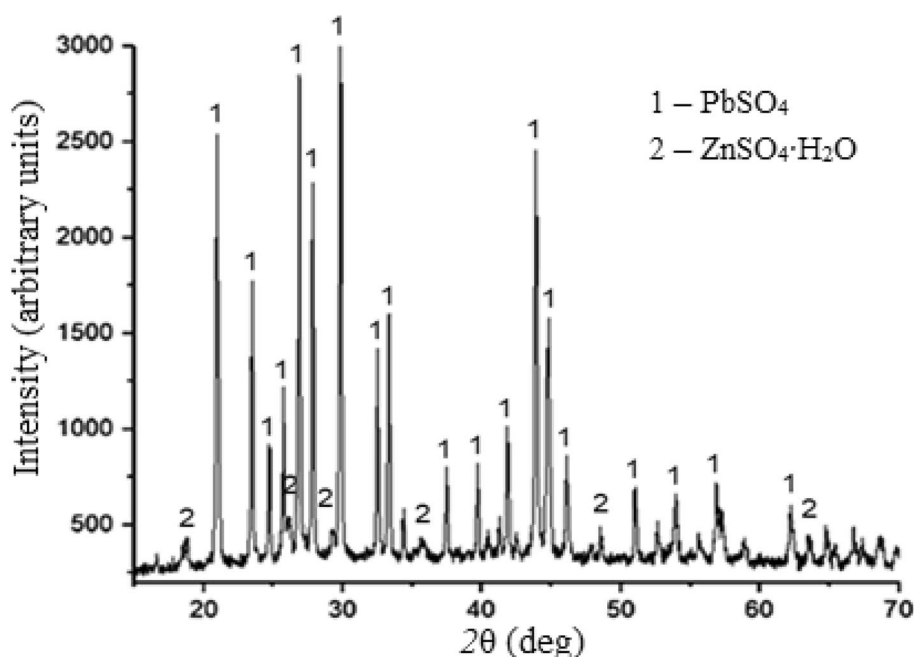
The results of studies of the microstructure and elemental content of dust, obtained using a SEM JED-2300 (Fig. 3), showed the presence of various compounds present in typical forms: dark gray (point 1, main components lead sulfates, zinc oxides arsenic  $As^{3+}$ ,  $As^{5+}$ , zinc and copper ferrites, silicates). The presence of the sulfide phase of non-ferrous metals is minimal; black (point 2, the main components in this area are lead sulfide and oxide, minor amounts of sulfides and oxides of copper and zinc); light gray (point 3 main components are oxides of lead, copper, zinc and arsenic). Sulfur is mainly present in the form of ( $SO_4^{2-}$ ) in the composition of lead and zinc sulfates. Iron oxides were found in small quantities: wüstite ( $FeO$ ), hematite ( $Fe_2O_3$ ) and magnetite ( $Fe_3O_4$ ).

The results of mapping dust samples shown in Fig. 4 show that arsenic oxides ( $As^{3+}$ ,  $As^{5+}$ , green dots in the figure) are scatteredly distributed among the oxides of lead (blue dots), copper and their sulfates (red dots) in greater or lesser quantities.

This is confirmed by the chemical composition of the detected phases. The established total content of arsenic oxide in dust in the form of  $As^{3+}$ , equal to approximately 8% (Fig. 3), indicates the presence of arsenic oxide in the form of  $As^{5+}$  in the original dust. At the same time, if we proceed from the total arsenic content in dust (13%, Table 1), then we can assume that in the original dust the proportion of the  $As_2O_3/As_2O_5$  ratio is 70/30%. The obtained result seems fundamental and requires considering the influence of  $As_2O_5$  on the total extraction of arsenic from dust under roasting conditions.

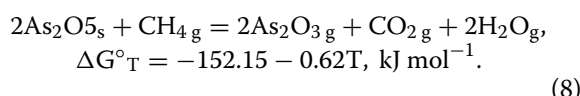
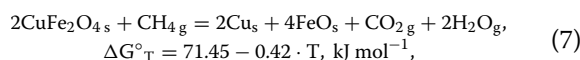
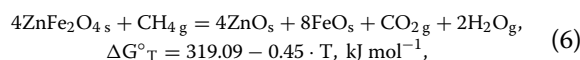
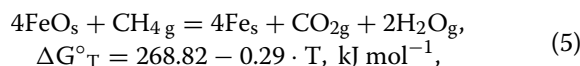
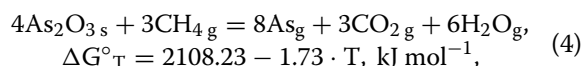
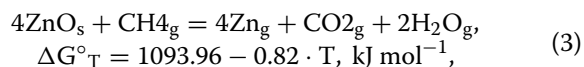
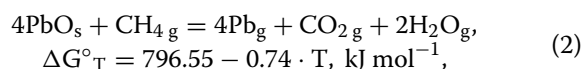
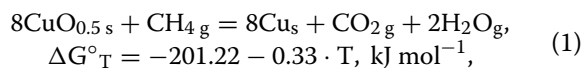
#### 3.2 Thermodynamics of reduction roasting of dust with natural gas

Thermodynamic analysis of the reduction roasting of dust with natural gas was carried out on the basis of generalized results of the elemental and phase composition of dust. The main goal of research into the reduction roasting



**Fig. 2** X-ray diffraction patterns of fine dust from a copper smelter

of dust with natural gas is to assess the possibility of maximizing the removal of arsenic and converting non-soluble compounds of non-ferrous metals (ferrites) in acid into readily soluble ones. During the studies, the behavior of lead and zinc sulfates was not addressed due to the extensive data available in the scientific literature on their behavior in various materials subjected to heating. It was also found that when calcining dust, lead and zinc sulfates are not reduced by natural gas due to the positive values of the Gibbs free energy ( $\Delta G^\circ_T$ ) throughout the studied temperature range of 500–1000 K. Based on this, the behavior of copper, lead, zinc, iron and arsenic during roasting can be described by the flow of the following main reactions (S – solid, G – gas):



The change in the Gibbs free energy ( $\Delta G^\circ_T$ , kJ mol<sup>-1</sup>) of Eqs. (1, 2, 3, 4, 5, 6, 7 and 8) from temperature is shown in Fig. 5.

As can be seen from Fig. 5, changes in the  $\Delta G^\circ_T$  of the reduction reactions of non-ferrous metal oxides (Eqs. (2) and (3)), arsenic oxide (3) and iron oxide (3) with natural gas, throughout the study temperature range 500–1000 K, are characterized by a positive value. The exception is the reduction reaction of copper oxide (1), which already at low temperatures (below 573 K) shows a high thermodynamic possibility of reducing copper oxide with natural gas,  $\Delta G^\circ_{573\text{K}} = -390 \text{ kJ mol}^{-1}$ .

It is easy to notice that during the dust roasting with natural gas, favorable conditions are created for the reduction of zinc and copper ferrites, as well as arsenic oxide (As<sup>5+</sup>) according to Eqs. (6), (7) and (8),



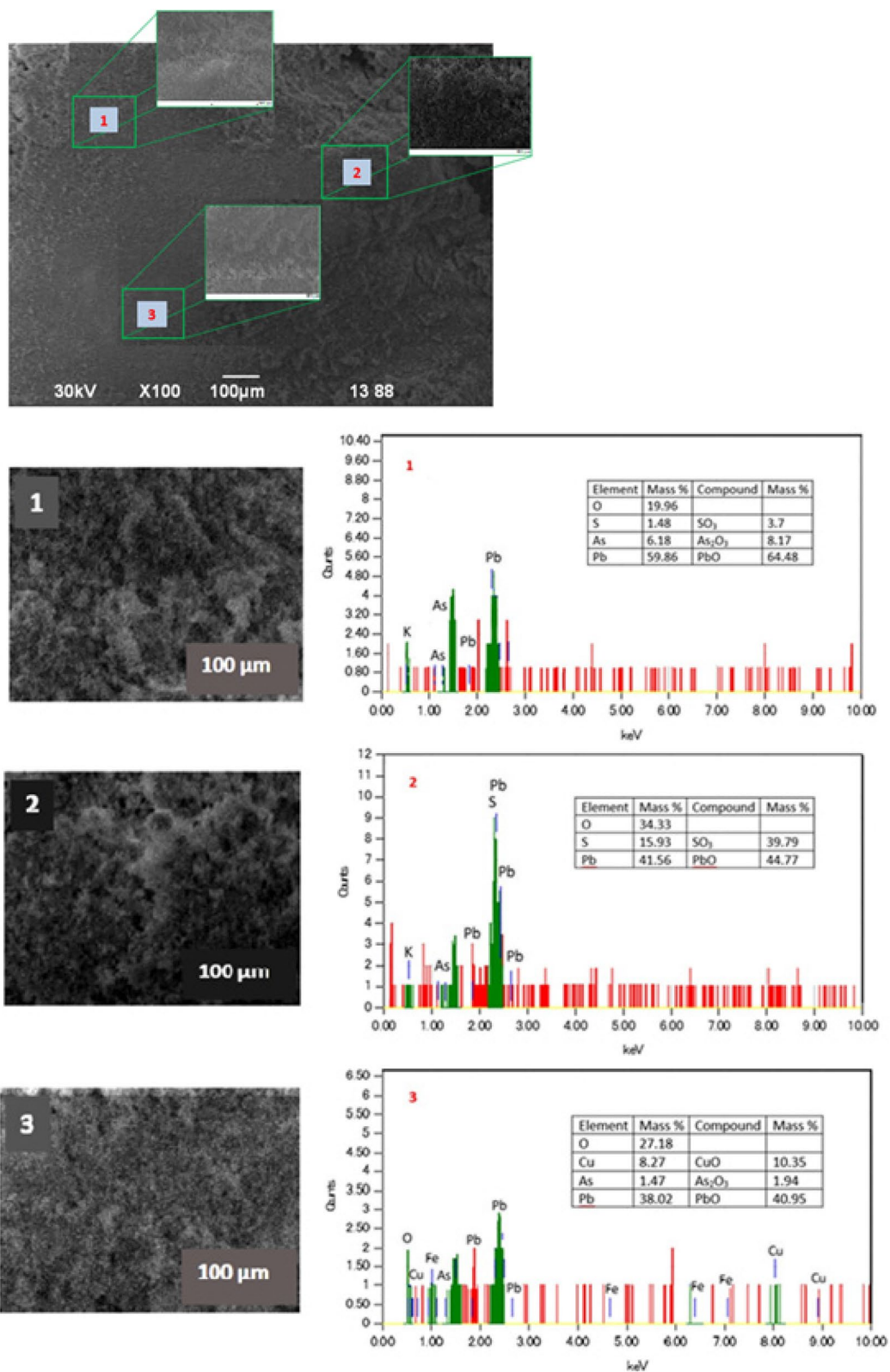


Fig. 3 Results of SEM-EDS analysis of copper smelter dust

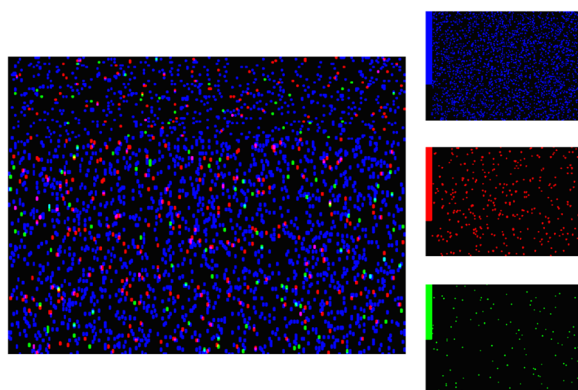


Fig. 4 Dust sample mapping results

respectively. Ferrites of copper and zinc, present in dust, do not dissolve in sulfuric acid, and when leached they turn into lead cake. This is indicated by the calculated positive values of the  $\Delta G^\circ$  of the reactions of interaction of copper and zinc ferrites with sulfuric acid over the entire studied temperature range. The transition of ferrites into lead cake, as results show, increases the loss of copper and zinc during leaching, which reduces their overall extraction into the final product.

Under conditions of reduction roasting of dust with natural gas, large negative values of the  $\Delta G^\circ_T$  of Eqs. (6), (7) and (8) indicate a high thermodynamic possibility of destruction of ferrites and the reduction of stable non-volatile arsenic oxide ( $As^{5+}$ ) to volatile arsenic oxide  $As_2O_3$  (Fig. 5). From a practical point of view,

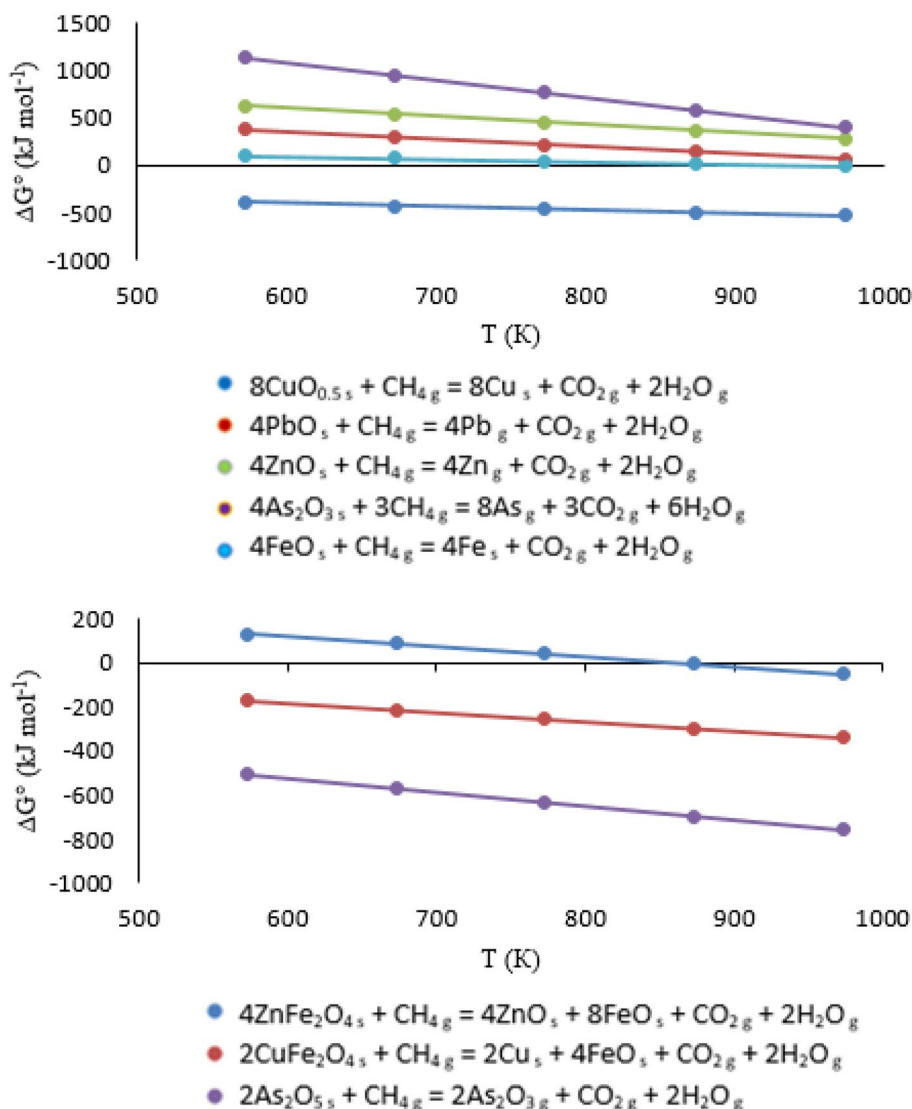


Fig. 5 Change in Gibbs free energy ( $\Delta G^\circ_T$ ) of Eqs. (1, 2, 3, 4, 5, 6, 7 and 8) depending on temperature

this means that as a result of the destruction of ferrites, copper and zinc turning into oxides that are easily soluble in acid. Consequently, with further leaching, the loss of copper and zinc from the lead cake will be reduced due to a more complete transition of copper and zinc oxides into solution. The high probability of Eq. (8) ensures maximum removal of arsenic from dust and the production of arsenic-free cinder with further high selective release of Pb, Cu, and Zn from it into commercial products.

Mamyachenkov et al. [25] show that to remove arsenic from fine dust from copper smelters, it is necessary to calcinate it under slightly oxidizing conditions. In this case,  $\text{As}_2\text{O}_3$  possessing high volatility (at 730 K, which is the boiling point, the vapor pressure of  $\text{As}_2\text{O}_3$  is 0.1 MPa) and it will pass into the gas phase. However, according to the authors, in the presence of oxygen in the system,  $\text{As}_2\text{O}_3$  can be oxidized to  $\text{As}_2\text{O}_5$ . Depending on the roasting conditions and the material composition of the dust,  $\text{As}_2\text{O}_5$  can remain unchanged in the cinder and interact with iron oxides to form iron arsenates:  $\text{Fe}_3(\text{AsO}_4)_2$  and  $\text{FeAsO}_4$  [25].

The creation of reducing conditions eliminates the possibility of the formation of intermediate iron arsenates and ensures maximum removal of arsenic from dust, both in the form of As(III) and through the reduction of As(V). This is confirmed by large negative values of the  $\Delta G^\circ_T$  of Eq. (8), which indicate a high thermodynamic probability of reduction of  $\text{As}_2\text{O}_5$  and removal of arsenic in the form of volatile gas  $\text{As}_2\text{O}_3$ .

### 3.3 Extraction of arsenic from fine dust by reduction roasting with natural gas

In carrying out experiments, the possibility of removing arsenic from dust by reduction with natural gas was studied. Two versions of the experiments were carried out: (1) by simply calcining the dust, similar to the experiments in [25] and (2) by reduction roasting of the dust with natural gas. The experiments were conducted under the same conditions: roasting duration – 20, 40 and 60 min. In all experiments, the temperature was constant and amounted to 500 °C. Each experiment was repeated three times. The results of three parallel experiments showed good reproducibility. The absolute deviation was 0.18, the error was 0.92%. After each experiment, the resulting cinder was weighed and subjected to elemental and phase analyses. The results of studies of the phase composition of cinder showed the presence of non-ferrous metals in the form of their oxides. The small amount of arsenic detected in the cinder can be neglected. The presence of copper and zinc ferrites was not detected in the cinder, which indicates their complete

destruction by natural gas with the formation of copper and zinc oxides.

During the experiments, it was not possible to accurately control the gas phase due to the high safety requirements when working with gases containing arsenic. Therefore, the gas phase released during the experiments was absorbed in a special vessel and neutralized.

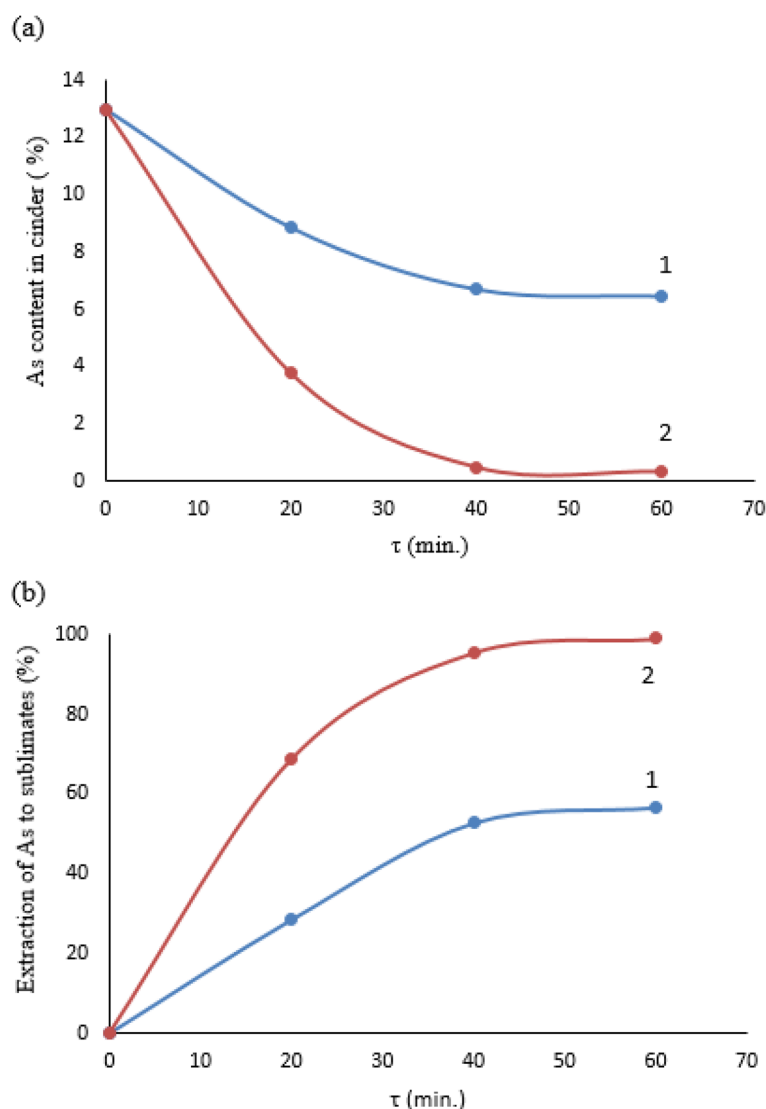
Determination of arsenic content was carried out based on the calculation of the difference between the amount of the initial and obtained products after the experiment, considering the arsenic content in them. Therefore, the extraction of arsenic into the dust was calculated according to the obtained data from difference.

Figure 6 shows the dynamics of changes in the arsenic content in the cinder depending on the duration of roasting.

With simple calcination of dust ( $t=500\text{ }^\circ\text{C}$ ), an increase in roasting time leads to a decrease in the arsenic content in the cinder. Minimum arsenic content of 6.72% is achieved at  $\tau=40$  min (Fig. 6a, curve 1). Increasing the roasting time to 60 min does not have a significant effect on the reduction of arsenic in the cinder: the arsenic content in the cinder, equal to 6.48%, shows almost the same value as at 40 min (the decrease is 0.24%). The calculated value of arsenic extraction from dust, shown in Fig. 6b, at  $\tau=60$  min is 50%. The obtained result does not agree with the data of [25], where a maximum arsenic recovery of ~98% was achieved at a temperature of 500 °C. However, a further increase in temperature sharply reduced the extraction of arsenic from dust. The authors explain the established pattern due to the oxidation reaction of  $\text{As}_2\text{O}_3$ , which leads to the formation of stable non-volatile pentavalent arsenic oxide.

By calcining the dust, maximum recovery of arsenic should be expected in the form of arsenic trioxide gas. If we take the proportion of arsenic present in the original dust in the form of  $\text{As}_2\text{O}_3$  equal to ~70% of the total arsenic content, then the  $\text{As}_2\text{O}_3$  content in the original dust will be 11%. The content of arsenic present in the original dust in the form of  $\text{As}_2\text{O}_5$  will be 6.13%. At a calcination temperature of 500 °C, pentavalent arsenic oxide does not sublime and remains in the solid phase. Consequently, the established arsenic content in the cinder is equal to 6.48% at  $\tau=60$  min, represents the sum of the content of  $\text{As}_2\text{O}_5$  present in the original dust and the minimum content of residual arsenic in the form of  $\text{As}_2\text{O}_3$  not removed by calcination, equal to 0.35%. The calculated value of arsenic extraction from dust in the form of  $\text{As}_2\text{O}_3$ , considering its residual content in the cinder, obtained at  $\tau=40$  min, will be 97.3%. The obtained result is quite consistent with the data from [25].





**Fig. 6** Dynamics of changes in arsenic content in cinder (a) and extraction of arsenic (b) from fine dust, depending on the roasting duration ( $\tau$ , min) at  $\tau=500$  °C: 1 – simple calcination of dust [25]; 2 – reduction roasting of fine dust with natural gas

In the case of the second option—reduction roasting of dust with natural gas, the nature of the curve of the dependence of the arsenic content in the cinder on time is steeper than in the first option. A sharp decrease in arsenic content from 13 to 3.76% was established already at  $\tau=20$  min (Fig. 6a, curve 2). Further increase in roasting time to  $\tau=60$  min reduces the arsenic content in the cinder to 0.32%, which corresponds to the almost complete removal of arsenic from dust. In contrast to the option of simply calcining the dust, the extraction of arsenic from the dust does not fall with increasing the roasting time, but remains at the maximum level. This indicates that complete arsenic extraction has been

achieved, equal to ~98%, with relatively short roasting time,  $\tau=60$  min (Fig. 6b, curve 2).

The obtained results show that at  $\tau=60$  min.; temperature – 500 °C, natural gas consumption is 1.5 times higher than the stoichiometric amount required for the reduction of  $As_2O_5$ , the maximum effect is achieved in extracting arsenic from dust—up to 99%, due to the complete reduction of  $As_2O_5$  with natural gas to the highly volatile form of arsenic  $As_2O_3$  with its further removal into sublimate. The experimental results fully confirm the conclusions about the high thermodynamic possibility of reduction  $As_2O_5$  and copper and zinc ferrites with natural gas. Thermodynamic calculations of the  $\Delta G^{\circ}_T$  of the reduction reactions of  $As_2O_5$  and

copper and zinc ferrites with natural gas, carried out using Chemistry 8.1.5, Outotec HSC software, showed high negative values of  $\Delta G^{\circ}_T$  at a temperature of 500 °C. Thus, for the reaction of reduction of  $As_2O_5$  with natural gas  $\Delta G^{\circ}_{500\text{ }^{\circ}C} = -632.61\text{ kJ mol}^{-1}$ ; for the reduction reaction of zinc ferrite,  $\Delta G^{\circ}_{500\text{ }^{\circ}C} = -48.95\text{ kJ mol}^{-1}$  and for the reduction reaction of copper ferrite,  $\Delta G^{\circ}_{500\text{ }^{\circ}C} = -253.71\text{ kJ mol}^{-1}$ .

#### 4 Conclusions

The possibility of effective arsenic removal from dust has been demonstrated by reduction roasting of fine dust from a copper smelter with natural gas. With roasting duration –  $\tau = 60$  min; natural gas consumption is 1.5 times higher than the stoichiometric amount required for the reduction of  $As_2O_5$ , temperature is 500 °C, almost complete up to 99% removal of arsenic from fine dust of a copper smelter has been achieved. Maximum extraction of arsenic from dust during reduction roasting is achieved through the sublimation of arsenic in the form of volatile  $As_2O_3$ , and due to the complete reduction of  $As_2O_5$  with natural gas to the volatile form of  $As_2O_3$  with further sublimation of arsenic. The residual arsenic content in the cinder after roasting is 0.31%. With the temperature above 500 °C, no changes in the extraction of arsenic into the gas phase are observed, but the consumption of electricity and gas increases, which is not practical from the point of view of the economic efficiency of the process.

The obtained results will be used for preliminary preparation of the industrial flowsheet for the processing of non-ferrous metallurgy dusts containing arsenic of various compositions and types.

Pre-treatment of dust by reduction roasting with natural gas will ensure the production of high-quality commercial products during subsequent processing operations of the resulting cinder. Removing arsenic from dust at the beginning of the technological scheme for its processing will eliminate the accumulation of arsenic in the overall technological scheme, which will significantly improve the technological, economic and environmental indicators of the technology as a whole.

#### Author' contributions

Nurlan Dosmukhamedov: Conceptualization, Methodology, Writing. Abdilmalik Takishov: Conceptualization, Supervision; Erzhan Zholdasbay: Investigation, Formal analysis, Visualization. Aidar Argyn: Resources, Writing, Review and editing. All authors read and approved the final manuscript.

#### Funding

The research was carried out within the framework of grant funding from the Science Committee of the Ministry of Science and Higher Education of the Republic of Kazakhstan for 2023–2025 in the priority area “Geology, extraction and processing of mineral and hydrocarbon raw materials, new materials, technologies, safe products and designs” of the project AP19676951:

“Development of resource-saving, a combined technology for the integrated processing of multicomponent dust from non-ferrous metallurgy to produce marketable products”.

#### Availability of data and materials

All data generated or analyzed during this study are contained within the article.

#### Declarations

#### Competing interests

The authors declare they have no competing interests.

Received: 16 November 2023 Accepted: 14 August 2024

Published online: 19 August 2024

#### References

- Moskalyk RR, Alfantazi AM. Review of copper pyrometallurgical practice: today and tomorrow. *Miner Eng.* 2003;16:893–919.
- Kobayashi Y, Hirano S. Distribution and excretion of arsenic metabolites after oral administration of seafood-related organoarsenicals in rats. *Metals.* 2016;6:231.
- Dosmukhamedov N, Kaplan V. Efficient removal of arsenic and antimony during blast furnace smelting of lead-containing materials. *JOM.* 2017;69:381–7.
- Zhong DP, Li L, Tan C. Separation of arsenic from the antimony-bearing dust through selective oxidation using CuO. *Metall Mater Trans B.* 2017;48:1308–14.
- Yang W, Tian S, Wu J, Chai L, Liao Q. Distribution and behavior of arsenic during the reducing-matting smelting process. *JOM.* 2017;69:1077–83.
- Chen C, Zhang L, Jahanshahi S. Thermodynamic modeling of arsenic in copper smelting processes. *Metall Mater Trans B.* 2010;41:1175–85.
- Swinbourne DR, Kho TS. Computational thermodynamics modeling of minor element distributions during copper flash converting. *Metall Mater Trans B.* 2012;43:823–9.
- Orac D, Laubertova M, Piroskova J, Klein D, Bures R, Klimko J. Characterization of dusts from secondary copper production. *J Min Metall B.* 2020;56:221–228.
- Dosmukhamedov NK, Fedorov AN, Zholdasbay EE, Argyn AA. Investigation of Cu, Pb, Zn, As, Sb distribution during the lead semiproducts and copper-zinc concentrate comelting. *Non-Ferrous Met.* 2020;1:8–14.
- Fry KL, Wheeler CA, Gillings MM, Flegel AR, Taylor MP. Anthropogenic contamination of residential environments from smelter As, Cu and Pb emissions: Implications for human health. *Environ Pollut.* 2020;262:114235.
- Gonzalez A, Font O, Moreno N, Querol X, Arancibia N, Navia R. Copper flash smelting flue dust as a source of germanium. *Waste Biomass Valori.* 2017;8:2121–9.
- Li Q, Pinto ISS, Zhao Y. Sequential stepwise recovery of selected metals from flue dusts of secondary copper smelting. *J Clean Prod.* 2014;84:663–70.
- Chen J, Zhang W, Ma B, Che J, Xia L, Wen P, et al. Recovering metals from flue dust produced in secondary copper smelting through a novel process combining low temperature roasting, water leaching and mechanochemical reduction. *J Hazard Mater.* 2022;430:128497.
- Adrados A, Merchan M, Obregon A, Artola A, Iparraguirre JA, Garcia de Cortazar M, et al. Development of a sustainable metallurgical process to valorize copper smelting wastes with olive stones-based biochar. *Metals.* 2022;12:1756.
- Lee H, Lee E, Jung M, Mishra B. Recovery of copper from flue dust generated in e-waste processing using physicochemical methods. *J Sustain Metall.* 2018;4:260–4.
- Cui W, Chen M, Zhao B. Pyrometallurgical recovery of valuable metals from flue dusts of copper smelter through lead alloy. In: Siegmund A, Alam S, Grogan J, Kerney U, Shibata E, editors. *PbZn 2020: 9th International Symposium on Lead and Zinc Processing.* Cham: Springer Cham; 2020. p. 539–47.

17. Lee H, Mishra B. Recovery of copper and precious metals and separation of lead from flue dust of electronic waste processing. *Min Proc Ext Met Rev.* 2020;41:153–61.
18. Vorotnikov AM, Lyzhin DN, Ipatova NS. Waste management system as an integral part of circular economy. *J Econ Res.* 2018;4:29–34 [in Russian]. <https://naukaru.ru/ru/nauka/article/24069/view> (Accessed 1 Aug 2024).
19. Montenegro V, Sano H, Fujisawa T. Recirculation of high arsenic content copper smelting dust to smelting and converting processes. *Miner Eng.* 2013;49:184–9.
20. Skopov GV, Belyaev VV, Matveev AV. Separate processing of Vanukov smelting electrofilter dusts and their withdrawal from circulation at Sredneuralsky copper smelter. *Tsvetnye Metally.* 2013;8:55–59 [in Russian]. <https://www.rudmet.ru/journal/1215/article/20614/> (Accessed 13 Aug 2024).
21. Mohagheghi M, Askari M. Copper recovery from reverberatory furnace flue dust. *Int J Miner Process.* 2016;157:205–9.
22. Guo XY, Yi Y, Shi J, Tian QH. Leaching behavior of metals from high-arsenic dust by NaOH–Na<sub>2</sub>S alkaline leaching. *T Nonferrous Metal Soc.* 2016;26:575–80.
23. Ke Y, Shen C, Min XB, Shi MQ, Chai LY. Separation of Cu and As in Cu-As-containing filter cakes by Cu<sup>2+</sup>-assisted acid leaching. *Hydrometallurgy.* 2017;172:45–50.
24. Sergeeva YF, Mamyachenkov SV, Sergeev VA, Karelov SV, Gallyamova NR. Hydrometallurgical processing technology of fine dusts of copper-smelting industry, using the complexing agent. *Tsvetnye Metally.* 2013;8:79–83 [in Russian]. <https://www.rudmet.ru/journal/1215/article/20619/> (Accessed 13 Aug 2024).
25. Mamyachenkov SV, Khanzhin NA, Anisimova OS, Karimov KA. Extraction of non-ferrous metals and arsenic from fine dusts of copper smelting using combined technology. *Non-Ferrous Met.* 2021;27:25–37 [in Russian]. <https://doi.org/10.17073/0021-3438-2021-5-25-37> (Accessed 1 Aug 2024).

### Publisher's Note

Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.