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DETERMINATION OF THE EFFECT OF THE ELECTROHYDRAULIC METHOD ON THE CRUSHING OF METALLURGICAL SILICON

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The object of the study is metallurgical silicon obtained from the «Tau-KenTemir» LLP plant, located in the Karaganda Region of the Republic of Kazakhstan. The problem that needs to be solved in the framework of this study is the high technological complexity, multi-stage nature and significant cost of traditional processes for cleaning metallurgical silicon from related chemical impurities.

An electrohydraulic unit was designed and assembled for the grinding of metallurgical silicon. The processing of metallurgical silicon was carried out with an increase in the discharge voltage of the storage device from 16 kV to 27 kV, the length of the interelectrode distance from 5mm to 11 mm, the capacitor capacity of 0.4 UF and the processing time of 5 min. Using the electrohydraulic method, particles of metallurgical silicon with an initial fraction of 3 mm, 5 mm and 10 mm were crushed to 0.074 mm. The results of crushing metallurgical silicon under the influence of the electrohydraulic method in a liquid medium allowed to determine the degree of grinding of the material.

Surface and quantitative analyses of powdered metallurgical silicon samples were performed using a scanning electron microscope and a Rigaku Simultix 15 spectrometer (Rigaku Corporation, produced in Japan).

The results obtained can be used in the study of the grinding characteristics of metallurgical silicon. High-purity silicon (polycrystalline and monocrystalline silicon) is widely used as a base material in the production of semiconductor devices and photovoltaic cells. It is also used in ferrous and non-ferrous metallurgy to produce alloys, as well as a raw material to produce high-purity silicon

Keywords: metallurgical silicon, electrohydraulics, cell, grinding, voltage, fraction, analysis, microscope, spectrometer

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1. Introduction

Currently, the importance of renewable energy sources is steadily growing. In this context, improving solar cell manufacturing technologies has become a top priority for the effective use of solar energy. Solar energy is one of the most modern, environmentally friendly, and renewable sources of energy. Solar panels, or photovoltaic cells, have become the cornerstone of the transition to sustainable energy sources. They allow direct conversion of sunlight into electrical energy. The use of solar energy has acquired an industrial scale and can provide heat and electricity not only for individual buildings, but also for entire cities. The electrophysical properties of photovoltaic modules depend on the nature of the raw materials, the concentration of impurities, and structural defects [1]. The main component of these devices is a silicon semiconductor, which possesses unique properties. Silicon is the most economically accessible semiconductor material.

To date, the level of development in the high-tech sector depends directly on the use of pure and ultra-pure silicon. This high-quality material (in the form of polycrystals and single crystals) serves as the primary basis to produce semiconductors and solar panel (photovoltaic cells). As for industrial (metallurgical) silicon, it is used as a component in the production of ferrous and non-ferrous metal alloys, as well as a raw material for producing ultra-high-purity silicon.

In nature, silicon occurs primarily in the form of compounds bound to oxygen-such as quartz, silicates, and other minerals [2].The production of metallurgical silicon with a purity of 98% is based on a carbothermic reduction process carried out in electric arc furnaces. In this process flow, the initial quartzite feedstock (SiO_2), containing approximately 46% silicon and 53% oxygen, is reduced using carbonaceous reagents [3].

Metallurgical silicon is a key component for the creation of aluminum-silicon alloys and is indispensable in the chemical synthesis of silicones. In addition, it is in demand in microelectronics and alternative energy, where it is used to produce semiconductors, chips and photovoltaic panels [4]. Metallurgical silicon is also an ideal raw material for use in solar cells. To turn technical metallurgical silicon (98–99% purity) into a high-tech material for solar energy or microelectronics, it must be purified from impurities (iron, aluminum, calcium, boron, phosphorus, etc.). All existing purification methods are divided into two large groups: chemical and direct physico-chemical [5].

The development of industry is directly related not only to the emergence of new materials, but also to the improvement of their processing technologies. From this point of view, special attention is paid to metallurgical silicon. The silicon grinding process is carried out in various mechanical mills: ball, cone, roller, etc. [6]. However, the designs of mechanical crushers are complex and expensive. One of the methods with a number of important advantages over traditional mechanical methods is the electrohydraulic method [7].

The consumption of metallurgical silicon, a non-metallic material and the foundation of modern industry, requires an increase in its production and raw material processing. In this regard, study aimed at developing electrohydraulic technologies is becoming particularly relevant. In this regard, electrohydraulic grinding of metallurgical silicon becomes the most profitable compared to existing methods [8]. Thus, the theoretical and practical development of electrohydraulic grinding is a difficult and significant step. Further developments in this area will not only optimize production processes and minimize environmental damage, but also bring significant economic benefits on an industrial scale.

2. Literature review and problem statement

The growing field of silicon solar cell applications requires a significant reduction in the cost of semiconductor silicon, which is currently produced using the classical method. In this direction, the authors in their study [9] consider the problems of obtaining high-purity silicon for solar cells. Alternative methods for obtaining solar-grade silicon are analyzed here: reduction of volatile silicon compounds, refining of metallurgical-grade silicon, reduction of silicon fluorides and reduction of silicon dioxide. However, this method has a number of serious technological, economic and environmental disadvantages that limit its effectiveness, especially when it comes to the production of high-purity silicon for solar energy and electronics.

According to the authors of [10], the growing demand for solar energy has led to a shortage of specialized silicon feedstock. To address this issue, chemical and metallurgical methods for producing solar-grade silicon (SoG-Si) from metallurgical-grade silicon (MG-Si) are being investigated. The authors note that chemical methods dominate the study and are preferred because they ensure higher purity of the final material. However, chemical methods are also harmful to the environment and expensive, and therefore further study is needed to address these issues.

The paper [11], the instability of the silicon feedstock market necessitates the adoption of low-cost methods for producing solar-grade silicon (SoG-Si). The authors consider metallurgical silicon (MG-Si, 98%) as a low-cost feedstock for subsequent purification to 99.99% purity using pyrometallurgical, hydrometallurgical, or electrochemical approaches. The paper emphasizes that the metallurgical method is a promising alternative to the Siemens process and provides a detailed analysis of three typical silicon refining methods. However, despite its ability to produce silicon of extreme purity, this method has a number of drawbacks: thermal losses, since the process takes place at very high temperatures (1000–1100°C), electricity consumption, as the production of 1 kg of high-purity silicon requires 60 to 120 kWh of electricity, and the formation of toxic silicon tetrachloride ($SiCl_4$) waste, which poses a risk of a catastrophic explosion.

The paper [12], a method of liquidation refining of metallurgical silicon (MGSi) using an AlSi alloy was proposed as a new technique for purifying silicon for solar cells. The study investigated the transformation mechanisms of impurities, particularly phosphorus (P) and iron (Fe). It was found that when silicon is alloyed with aluminum, phosphorus migrates into the Al-Si eutectic, forming an Al-Si-Ca-P phase, while iron forms the α-Al8SiFe2 skeletal phase. Thus, the authors' results of the study demonstrated that the mechanism of removal of these elements is not limited to segregation alone but is characterized by the interaction (recombination) of certain elements with the formation of distinct mixed phases. When using the centrifugal separation method during the precipitation process, the average separation efficiency for the Al–45% Si system was 75.73%, and the recovery rate was 82.52%. This allows for a significant reduction in aluminum and acid consumption compared to traditional methods. However, this method leads to silicon contamination with aluminum and the generation of a large amount of acidic waste during its removal.

The paper [13], a combined method of purification of metallurgical silicon (MG-Si) with Mg-Si alloy by refining and acid leaching is proposed. The process consists of the stages of electromagnetic crystallization, vacuum evaporation of magnesium and acid leaching. As a result of magnesium evaporation, a porous silicon structure of nano- and micrometers was formed, which made it possible to effectively remove impurities (B, P, Fe, Ca, etc.) at the next stage to a level of less than 1ppm. The result is pure silicon powder with a purity of more than 99.995%. This method is economical and efficient to produce silicon for solar cells (SoG-Si) because it recycles magnesium and allows it to be used cyclically. However, despite the high efficiency of removing a number of impurities (especially boron and phosphorus), this method has several significant disadvantages. During the recrystallization of the Mg-Si system, the predominant volume of silicon is bound within the eutectic and intermetallic compounds (in particular, magnesium silicide Mg_2Si). In addition, subsequent acid leaching, aimed at dissolving the magnesium matrix, leads to the complete removal of some of the fine silicon, which is washed out along with the sludge. This significantly worsens the final yield of a useful product. Various crushing plants are used to carry out high-quality crushing of metallurgical silicon within the framework of the methods described above.

The paper [14] analyzes the main components of a ball mill (drum, ball charge, drive and gearbox, and packing), and examines particle size, operating conditions, and the role of cooling systems in achieving optimal grinding results. As part of study in this area, new trends in ball mill design were examined – the introduction of modern materials, automation, multisensor systems, energy efficiency, and hybrid solutions. According to the authors, selecting the right mill in accordance with specific production conditions will improve the efficiency of ore processing and significantly reduce production costs. The main drawback of modern ball mills is their technological "coarseness" and economic inefficiency in terms of energy consumption. Nevertheless, this method has a number of disadvantages. The main ones are high energy consumption, over-grinding of the final product and the risk of contamination with metallic impurities, which negatively affects the quality of the raw material and prevents the required purity of the final product from being achieved.

A way to overcome these difficulties can be the processing of metallurgical silicon, which minimizes the over-grinding of the finished product and ensures its high purity. In order to increase the efficiency of solar energy, one of the urgent issues is the expansion of the raw material base and the introduction of alternative methods.

The authors of [15] present a method for calculating the parameters of a high-voltage discharge channel (pressure, radius, expansion rate) of electric discharge machines for the destruction of non-metallic materials. This method allowed to study the influence of parameters (inductance, voltage, and capacitance) on the hydrodynamic parameters of the discharge channel and the pressure wave generated. The effective fracture zone has been determined, which depends on the cycling parameters, the strength characteristics of the material being destroyed, and the electrical conductivity of the discharge medium. Recommendations on the choice of technological modes of electric discharge machines for the disintegration of non-metallic materials are proposed. Despite its widespread use, this analytical approach has a number of serious drawbacks and assumptions that reduce the accuracy of predicting the actual efficiency of electric discharge machines.

In paper [16], the authors' study demonstrates that the electrical discharge process, developed through pilot-scale industrial trials, and the equipment required for its implementation ensures the effective decomposition of metallurgical silicon. This technology enables the production of raw materials in the specific fractions required for the manufacture of high-purity monocrystalline silicon. Instead of traditional mechanical methods for grinding metallurgical silicon, an electrical discharge method was used, which will preserve the purity of the final product and increase the efficiency of the process.

The results of these studies confirm that electrohydraulic crushing of metallurgical silicon demonstrates the highest efficiency among existing methods. The use of the electrohydraulic method for crushing metallurgical silicon requires a detailed study of the effect of electrical pulse parameters on the disintegration process.

The absence of a comprehensive physico-technical model of electrohydraulic grinding of metallurgical silicon, which establishes the relationship between the parameters of an electric pulse (voltage, capacitance, frequency), the geometry of the discharge system and the physico-chemical properties of the resulting powder (granulometric composition, degree of purity, structural defects). Without solving this problem, it is impossible to create a controllable and reproducible technological process. Changing the parameters "at random" leads either to excessive wear of the equipment and contamination of silicon, or to low productivity, which devalues all the theoretical advantages of the electrohydraulic method over the mechanical one.

All this supports the argument for conducting research works is needed, including experimental processing of raw materials while varying the voltage capacity of the capacitor banks of the installation, as well as the total number of discharges supplied.

3. The aim and objectives of the study

The aim of this study is to identifying the effect of the electrohydraulic method on the grinding of metallurgical silicon. The results of this study may contribute to the development of devices for grinding metallurgical silicon.

To achieve this aim the following objectives are addressed:

– to obtain the dependence of the degree of crushing of metallurgical silicon on the gap distances;

– to determine the elemental composition of metallurgical silicon samples using a Rigaku Simultix 15 spectrometer.

4. Materials and Methods

The object of the study is metallurgical silicon obtained from the metallurgical silicon production plant of Tau-Ken Temir LLP, located in the Karaganda region of the Republic of Kazakhstan (Fig. 1).

The main hypothesis of the study is that varying the gap distances in an air-gap arrester allows for the regulation of the breakdown voltage and the stiffness (steepness) of the generated electrical pulse. This directly influences the shock wave amplitude in the working cell and makes it possible to control the dispersion of the silicon powder while maintaining control over its elemental composition.

In the course of the study, the following assumptions were made: changing the gap in the air arrester is a key tool for dosing the energy that initiates the subsequent water hammer, the air gap at a fixed distance breaks through at the same threshold voltage throughout the series of pulses, intensification of grinding (due to due to changes in the parameters of the arrester) will not cause avalanche-like contamination of silicon by erosion products of the submersible working electrodes.

The following simplifications were adopted in the course of the study:

– idealized conditions in the air gap, without taking into account the ionization of the air from previous discharges and the local heating of the arrester electrodes. It is assumed that each new breakdown occurs in the same gaseous medium, although in fact the air between the pulses does not have time to fully deionize;

– constancy of the geometry of the working area: the distance between the working electrodes directly in the liquid medium and the volume of the working fluid are considered strictly constant. Only the gap on the air arrester varies.

For smelting metallurgical silicon, to provide high-quality raw materials, the Aktas quartz deposit [17], owned by Silicon mining LLP, is used. The deposit is in the Ulytau district of the Karaganda region, 130 km northwest of the city of Zhezkazgan. The high purity of quartz in this deposit makes it possible to effectively use it as a raw material for smelting highly labeled technical silicon.

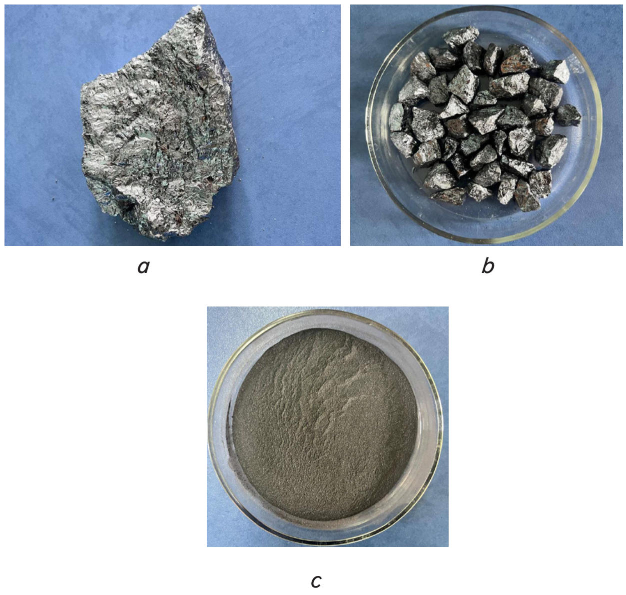


Fig. 1. Samples of metallurgical silicon: *a* – sample piece, d = 62 mm; *b* – mechanically crushed, d = 10 mm; *c* – electrohydraulic method, d < 0.074 mm

Since the initial size of the pieces of metallurgical silicon was too large, it was first subjected to mechanical crushing to the required fraction. Various fractions of the crushed material were measured with a caliper and selected into equal-weight samples. Before loading into the working cell, the silicon mass was determined on an electronic scale. The granulometric composition of the obtained powder was evaluated using standard laboratory sieves.

The experiments were conducted at various voltages ($U = 16–27$ kV) across the switching device and at various gap distances ($l_p = 5–11$ mm). The degree of grinding of metallurgical silicon K (%) after electrohydraulic treatment is determined by the following equation

$$K = \frac{m}{m_0} 100\%,$$

where m and m_0 – the masses of the metallurgical silicon fractions before and after electrohydraulic treatment.

A review of scientific publications in recent years shows a growing interest in the application of the electrohydraulic method. The processes of disintegration and crushing of solid fractions by creating high pressure at the shock wave front are carried out by means of an electric discharge in an aqueous solution of metallurgical silicon. In addition, to study the effect of the electrohydraulic method on the efficiency of crushing metallurgical silicon, an experimental installation was developed and assembled (Fig. 2).

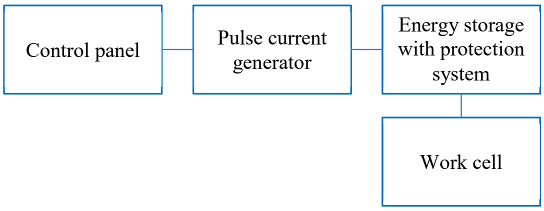


Fig. 2. Block diagram of a plant for the grinding of metallurgical silicon

Fig. 3 below shows the working cell of a unit designed for the grinding of metallurgical silicon. To ensure that the working cell is resistant to shock waves generated in the liquid medium by the electrohydraulic effect, it was constructed from a sturdy steel cylinder with a diameter of d = 100 mm and a height of h = 100 mm, and its cover was made of fluoroplast.

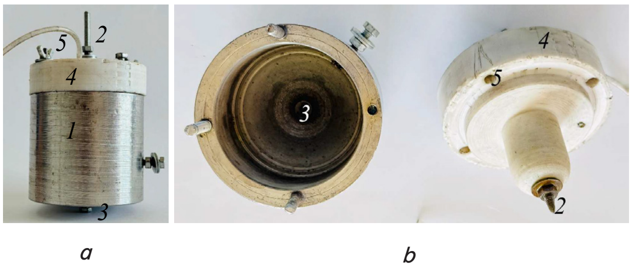


Fig. 3. Working cell of the experimental setup for the reduction of metallurgical silicon: *a* – main housing; *b* – working electrodes; 1 – cylindrical housing with a diameter of 100 mm; 2 – positive electrode with a diameter of 4 mm; 3 – negative electrode; 4 – fluoroplast cover with a diameter of 100 mm; 5 – fasteners

Study using this method helps to accelerate the process of grinding metallurgical silicon. Metallurgical silicon produced using the proposed method is used in the manufacture of solar cells. This method helps to reduce the impurity content in metallurgical silicon. The electrohydraulic method is used for crushing large pieces of rock in mines and quarries, crushing various materials [18], processing organic waste [19], and producing fuel from coal, where the material was processed using an electric pulse method with different voltage values, number of pulses, capacitor capacity, and pulse frequency [20].

Basic principles when an electric discharge occurs in a liquid medium, a shock wave is formed. This wave destroys silicon, crushing it to fractions of the required size. During operation, it is possible to control the particle size and selectively separate impurities. The main advantage of the electrohydraulic method is the accuracy of the size of the resulting particles and the reduction of impurities. The method is environmentally friendly. It makes the crushed material more convenient for subsequent chemical cleaning and has higher energy efficiency compared to mechanical methods.

The surface structure of powdered metallurgical silicon was studied using a Tescan Mira3 scanning electron microscope (manufactured in the Czech Republic). The technique is based on scanning the sample surface with a focused electron beam under high vacuum conditions. At an accelerating voltage of 30 kV, it also allows detailed investigation of nanostructured powder elements up to 1.0 nm [21].

A Rigaku Simultix 15 spectrometer (Japan) was used for quantitative analysis of powdered metallurgical silicon samples. The technique is based on wave dispersion X-ray fluorescence analysis and is used to determine the elemental composition of silicon (including trace elements). The sample is irradiated with a powerful beam of primary radiation from an X-ray tube [22]. The power of the X-ray tube is up to 4 kW, which guarantees high radiation intensity and low detection limits for light and heavy elements. Provides the possibility of simultaneous analysis of up to 30–40 elements in one sample.

5. Results and discussion the effect of the electrohydraulic method on the crushing of metallurgical silicon

5. 1. The main results of processing metallurgical silicon using the electrohydraulic method

Tables 1–3 present the results of experiments on the grinding of metallurgical silicon using the electrohydraulic method.

These experiments were conducted under the following constant conditions: initial silicon particle sizes of 3, 5, and 10 mm; gap distances l_p = 5–11 mm; capacitor bank capacitance C = 0.4 μF; initial sample mass m_0 = 50g; and processing time of 5 minutes. The interelectrode distance inside the working cell was l_e = 6 mm. The minimum size of the resulting metallurgical silicon was less than 0.074 mm.

Table 1

Dependence of the degree of grinding of metallurgical silicon on the gap distances l_p, mm (d_0 = 3 mm, C = 0.4 μF)

d, mm	d_0 = 3 mm			
	l_p = 5 mm	l_p = 7 mm	l_p = 9 mm	l_p = 11 mm
	k, %	k, %	k, %	k, %
d < 0.074	1	1.6	2.8	3.8
0.074÷0.18	5.4	10.2	24	34.4
0.18÷1	13.6	18.4	26.8	25.2
1÷2	79.2	68.8	45	35.4

Table 2

Dependence of the degree of grinding of metallurgical silicon on the gap distances l_p, mm (d_0 = 5 mm, C = 0.4 μF)

d, mm	d_0 = 5 mm			
	l_p = 5 mm	l_p = 7 mm	l_p = 9 mm	l_p = 11 mm
	k, %	k, %	k, %	k, %
d < 0.074	0.8	1.4	2	3.2
0.074÷0.18	1.2	2	3.2	4.2
0.18÷1	11.4	9.8	15	15.4
1÷3	8.4	12.8	11	8.4
3÷5	76.2	72.6	68.2	66.2

Table 3

Dependence of the degree of grinding of metallurgical silicon on the gap distances l_p, mm (d_0 = 10 mm, C = 0.4 μF)

d, mm	d_0 = 10 mm			
	l_p = 5 mm	l_p = 7 mm	l_p = 9 mm	l_p = 11 mm
	k, %	k, %	k, %	k, %
d < 0.074	1.2	4.6	6.4	10.6
0.074÷0.18	5.6	11.2	6.6	8.8
0.18÷1	20.6	23.4	21.8	25.4
1÷3	3	7.4	4	5.4
3÷5	7.6	6.6	10	6.2
5÷7	14.4	9	15.4	9.4
7÷9	44	36.6	34.4	33.2

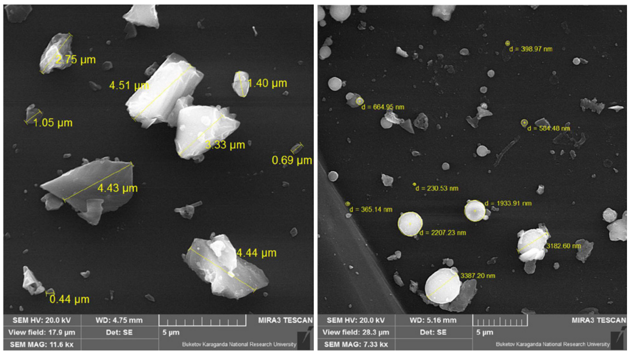
From the data in Tables 1–3, with an increase in the bit spacing in the switching device, the degree of silicon grinding increases.

5. 2. Results of surface and quantitative analysis of metallurgical silicon samples

Subsequent studies were conducted using electron microscopy techniques, which included surface analysis, while quantitative analyses of the elemental composition of metallurgical silicon samples-ground by mechanical and electrohydraulic methods – were performed using a Rigaku Simultix 15 spectrometer.

Metallurgical silicon contains various chemical impurities. Isolating these impurities in their pure form requires a complex and costly processing procedure involving multistage processes of disintegration, grinding, and chemical purification. In this regard, the electrohydraulic method of grinding metallurgical silicon can be noted as an effective alternative.

Fig. 4 shows scanning electron microscope images of metallurgical silicon obtained from the Tau-Ken Temir LLP plant (Republic of Kazakhstan) and ground using mechanical and electrohydraulic methods, captured using a Tescan Mira3 (SEM) scanning electron microscope. The surface images were obtained at 5 μm magnification.



a *b*

Fig. 4. Electron micrographs of powdered metallurgical silicon: *a* — mechanical; *b* — electrohydraulic

Metallurgical silicon contains impurities in the form of both minerals and chemical compounds. Obtaining pure silicon (Si) requires a complex and costly processing procedure that includes several stages of disintegration, grinding, enrichment, and chemical purification. One such method is the electrohydraulic grinding of raw materials.

Table 4 presents the results of quantitative analysis of metallurgical silicon ground by mechanical and electrohydraulic methods, conducted using a Rigaku Simultix 15 spectrometer.

Table 4

Quantitative analysis of metallurgical silicon crushed by mechanical and electrohydraulic methods

Impurities	The mechanical method	Electro-hydraulic method
Si	98.12%	99.40%
Fe	1.48%	0.35%
Al	0.19%	0.08%
Ca	0.035%	0.030%
Ti	0.073%	0.027%
P	0.0044%	0.0043%

Table 4 shows that the raw material under study contains a fairly high content of the main element (silicon Si).

6. Discussion of the results of the study of the effect of the electrohydraulic method on the grinding of metallurgical silicon

In contrast to the classical methods of mechanical grinding (cone mills, drum mills, etc.), considered in the review [23], where the working organs of the mills wear out after processing, and heavy metals (primarily iron and chromium) appear in the silicon. And subsequently, deep and expensive acid purification is required to extract these metals. And electrohydraulic grinding practically eliminates direct contact of silicon with the metal parts of the installation (with the exception of the electrode area). This result makes it possible to obtain metallurgical silicon powder, while maintaining the initial purity of the product (or even increasing it due to the associated removal of surface contaminants), minimizing the secondary grinding of undesirable impurities. Therefore, mechanical and chemical methods sometimes require high costs. In addition, the advantages of our technology are the efficiency of reducing the negative impact on the environment (no need for chemicals and minimization of waste).

In addition, the authors [24] used electric pulse treatment to obtain environmentally friendly coal-water fuel. The main focus of this work is on the positive electrode, which must be resistant to high temperatures and aggressive conditions that occur during pulse processing. However, the proposed electrodes work effectively in cells for crushing coal or coal sludge. However, crushing metallurgical silicon requires a special cell shape and an optimal electrode design.

Table 1 shows that with an initial fraction with a diameter of $d_0 = 3$ mm and an inter-bit distance of $l_p = 5$ mm, the degree of grinding of small particles (less than 0.074 mm) corresponds to –1%, and with an increase in the inter-bit distance of $l_p = 11$ mm, the degree of grinding increases by 3.8%.

The results of the study in Table 2 show that with an initial fraction with a diameter of $d_0 = 5$ mm and an inter-bit distance of $l_p = 5$ mm, the yield of small fractions (less than 0.074 mm) was 0.8%, with an increase in the inter-bit distance to $l_p = 11$ mm, the proportion of small particles in the grinding product increases to 3.2%.

Also, the results shown in Table 3 show that with an initial fraction with a diameter of $d_0 = 10$ mm and the length of the gap distances $l_p = 5$ mm, the degree of grinding of fine particles is 3.2%, and with an gap distances $l_p = 11$ mm, the degree of fine particles increases to 10.6%.

In the experiment, the initial particle size for producing particles smaller than 0.074 mm was 3 mm, 5 mm, and 10 mm (Table 1–3). As the data show, the most optimal particle size is 10 mm. Based on existing experience, the energy consumption for a mechanical crusher when grinding 10 mm particles is higher than that of an electrohydraulic installation. Tables 1–3 show that the degree of grinding of metallurgical silicon increases sharply as the for the gap distances is $l_p = 11$ mm increases. According to the results of the study, the optimal value for the gap distances is $l_p = 11$ mm. The obtained results make it possible to determine the optimal values of the inter-discharge distance for conducting silicon research.

Before studying the metallurgical silicon structures, the samples were crushed mechanically and using electrohydraulic force. The diameters were 0.074 mm. Fig. 4 shows that the particles of metallurgical silicon produced by mechanical grinding have an angular shape with clearly defined edges (Fig. 4, *a*), whereas those produced by electrohydraulic grinding (Fig. 4, *b*) have a granular shape. As can be seen from Fig. 4, *a*, during mechanical grinding of metallurgical silicon, the diameter of large particles is 4.51 μm, and the diameter of particles is 0.44 μm, which means that the mechanical method does not allow obtaining the required fraction, however, when grinding by the electrohydraulic method, the maximum particle diameter is 3.387 μm, the particle diameter is 230.53 nm. The electrohydraulic method allows introducing the required fraction.

Further analysis shows that when processing metallurgical silicon using the electrohydraulic method (Table 4), the content of the main element (silicon) increased from 98.12% to 99.40%, i.e. the proposed method not only allowed to increase the concentration, but also decreased the concentration of other impurities: titanium (Ti) – from 0.073% to 0.027%, calcium (Ca) – from 0.035% to 0.030%, aluminum (Al) – from 0.19% to 0.08%, phosphorus (P) – from 0.0044% to 0.0043% and iron (Fe) – from 1.48% to 0.35%.

Results of the study showed that after electrohydraulic processing of metallurgical silicon, the base element concentration is 99.40%. Using a source from Tau-Ken Temir LLC (Karaganda Region, Republic of Kazakhstan) is cost-effective and advantageous due to the high purity of the material, allowing it to be implemented into production without additional purification.

It is worth noting that the peculiarity of the proposed method is as follows: the use of the electrohydraulic method not only allows for the grinding of metallurgical silicon, but is also one of the most promising ways to remove unwanted impurities from it. In particular, the observed decrease in the iron content – Fe (%) – from 1.48 to 0.35 (Table 4) shows that this method is more effective for obtaining high-quality silicon.

High-purity metallurgical silicon is used in the production of silicon plates for solar cells, in discrete semiconductor devices, where the purity requirements are slightly lower than in integrated microcircuits (for example, powerful diodes, thyristors).

In order for the use of pure metallurgical silicon to be economically and technologically justified, strict control of critical impurities (boron and phosphorus), stability of the chemical composition and environmentally safe processing is necessary.

The expected economic effect is to reduce the cost of processing metallurgical silicon to produce pure silicon. This is achieved through the use of electrohydraulic treatment, which reduces the amount of subsequent preparatory work.

The proposed electrohydraulic method for obtaining an aqueous suspension of silicon does not require high costs to obtain a powder of a given dispersion and is technologically economical.

A number of significant technological, economic and environmental constraints can be identified, which must be taken into account both when scaling up the technology and in future theoretical work. The electrohydraulic method is, in itself, a chemical separation method; therefore, its potential for the deep removal of boron and phosphorus is strictly limited by the initial distribution of impurities within the silicon matrix. For the solar energy sector, even parts per million of iron, copper or tungsten impurities are of critical importance. The limitation lies in the need to source ultra-pure materials for the electrodes themselves, which is technologically challenging. There is a limit to the degree of grinding beyond which the energy expenditure per pulse ceases to result in effective particle disruption due to the damping effect of fine powder in a liquid. The transition to continuous industrial production with high throughput (t/h) is an extremely complex engineering challenge, which is usually overlooked in laboratory studies. During the silicon grinding process, water becomes saturated with ultradisperse silicon dust, colloidal solutions and ions of leached impurities. The production process can only be described as 'environmentally friendly' once the issue of water recycling and the filtration of these sludges has been resolved, which in itself is a polluting and energy-intensive process.

In theory, it is necessary to take into account that the conductivity of the medium changes from pulse to pulse (due to the release of impurities from silicon into water and heating), which changes the parameters of the discharge itself. Theoretical models that do not take this dynamic into account will not be applicable in practice.

The disadvantages of this study include the wear of the working electrode of the cell, as the length of the electrode decreases during multi-faceted work. In this regard, it is necessary to select the electrode material for multiple applications.

The main difficulty lies in manufacturing the step-up transformer required for this work. Not every industrial enterprise is willing to implement alternative systems for crushing and grinding metallurgical silicon.

7. Conclusions

1. The dependences of the degree of grinding of metallurgical silicon on the inter-discharge distance are obtained. The optimal parameters were determined: the diameter of the initial fraction $d_p = 10$ mm, the length of the gap distances $l_p = 11$ mm.

2. Surface analysis using a Mira3 Tescan scanning electron microscope (SEM) and the content of the elemental composition of metallurgical silicon samples crushed mechanically and electrohydraulic method on a Rigaku Simultix 15 spectrometer were determined. When grinding metallurgical silicon mechanically, the diameter of small particles was 0.44 microns, and the electrohydraulic method of small particles was 230.53 nm. The results of the investigation of the surface of metallurgical silicon obtained using the Mira3 Tescan (SEM) scanning electron microscope show that the electrohydraulic method makes it possible to obtain nanoparticles. The purity of silicon increased from 98.12% to 99.40% due to the effective removal of impurities: Fe (from 1.48% to 0.35%), Al (from 0.19% to 0.08%), Ti (from 0.073% to 0.027%), Ca (from 0.035% to 0.030%) and P (from 0.0044% up to 0.0043%).

Conflict of interest

The authors state that there is no conflict of interest regarding this study, including financial, personal, authorial or otherwise, that could affect the study and its results presented in this article.

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Data availability

Data will be provided upon reasonable request.

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Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies in creating the submitted work.

Authors' contributions

Bekbolat Nussupbekov: Conceptualization, Methodology, Investigation, Writing – review & editing, Visualization, Supervision; **Gulden Bulkairova**: Methodology, Investigation, Writing – original draft, Supervision; **Gulzira Mussina**: Validation, Investigation, Writing – review & editing, Visualization; **Saule Sakipova:** Methodology, Investigation, Writing – original draft, Supervision; **Aizada Muratova:** Validation, Investigation, Visualization.

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