Kinetics of cyclone dust flotation separation in polluting industries

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Abstract. This article describes the study of the kinetics of flotation separation of silicate and carbon dust phases of silicon cyclones. For research, we selected 50 samples of dust gas purification production of silicon to the Silicon situated in the city of Shelekhov of the Irkutsk region. The dust caught by bag filters can be applied as an additive in concrete, rubber products or subjected to processing for expansion of a scope of application. Silicate and carbonate phase of the cyclone dust silicon production separately represent the products in demand. The cost depends on the degree of purity, structure and particle size distribution. Describes the basic dependence of the flotation nanoscale this part of carbon and microsilica. Micro particles inherent in the formation of stable heterogeneous conglomerates. Dissimilar particles can both be introduced into the foam product and remain in the chamber reducing the quality of concentrates. To solve this problem, pulp conditioning is used with the help of sonochemical installations, which contributes to the separation of a large number of conglomerates. The effect of aeration on the flotation process of nanoscale particles is described. Conducting experiments on laboratory experimental flotation machine in different modes and with different flotation reagents. A method of conditioning the pulp, which increases the efficiency of flotation and, as a consequence, the quality of the output products. The dependences of the foam layer height on the concentration of the foaming agent, the dependence of the quality and quantity of the output products on the time and flotation regime are constructed. Important conditions for providing a high degree of separation of micro-sized media are determined. This solution was developed for the enrichment of the cyclone dust gas purification silicon. The study identified the main features of the flotation separation of silicate and carbon phases of cyclone dust. The technical solutions allowing to make effective separation despite the revealed features are offered. Application of this technology leads to reduction of sludge accumulation near silicon plants and production of innovative modifiers for various industries.

1. Introduction
Modern dry gas cleaning units at industrial silicon production plants have two successive stages - dust deposition in cyclones-dust collectors and final dust collection using bag filters.

The dust captured by bag filters can be used as an additive in concrete [1-4], rubber products or processed to expand the scope of application [5-7]. Dust caught by cyclones (hereinafter referred to as cyclone dust) is today considered a waste of 3-4 class of hazard and is subject to storage in sludge fields. This article will focus on a method for processing cyclone dust in order to obtain valuable products.
For the experiments, the results of which are presented in this work, dust was used, caught by the first stage of dry gas cleaning of the plant for the production of technical silicon CJSC "Silicon", located in the town Shelekhov, Irkutsk region [8-13]. 50 samples were taken and examined, in tables 1 and 2 the average results of analyzes of the selected samples are presented.

**Table 1.** Composition of the crystalline phase of cyclone dust according to XRD results (average of samples).

| No | Phase                  | Content, % |
|----|------------------------|------------|
| 1  | SiC (Moissanite)       | 20         |
| 2  | SiO₂ (Quartz)          | 60         |
| 3  | SiO₂ (Cristobalite)    | 10         |
| 4  | Si (Crystalline)       | 5          |
| 5  | C (Crystalline)        | 5          |

**Table 2.** Composition of cyclone dust.

| No | Compound  | Content, % |
|----|-----------|------------|
| 1  | C         | 20         |
| 2  | SiO₂      | 68         |
| 3  | SiC       | 10         |
| 4  | Na₂O      | 0.059      |
| 5  | MgO       | 0.059      |
| 6  | Al₂O₃     | 0.24       |
| 7  | K₂O       | 0.24       |
| 8  | CaO       | 1.19       |
| 9  | Fe₂O₃     | 0.21       |

The first stage of dry gas cleaning is represented by a battery of cyclones-dust collectors, the capacity of the battery is about 500 thousand m³/hour for the gas off-gas from the furnaces. The dust content of the gas and dust flow is, on average, 3-4 g/m³. The total amount of dust captured by cyclones per year is 15 thousand tons. After catching, the dust enters the receiving hopper of the cyclone battery, from where the dust is periodically unloaded for further burial at the landfill. The most suitable place for sampling of raw materials is the bunker of the cyclone battery of the first stage of gas cleaning.

2. **Sampling and preparation of raw materials for flotation separation**

Often, in the process of obtaining technical silicon, mandatory technological measures are carried out, associated, for example, with the replacement of consumable elements of the furnace or other routine maintenance. Also, unstable operation of the furnaces is possible, caused by the deviation of the quality of the charge materials. At moments of deviation from the normal technological regime, the properties and composition of the gas and dust flow removed from the furnaces may significantly differ from the nominal values. To take representative samples of the material, it is necessary to have information about the current mode of operation of the entire production cycle. Sampling was carried out from the receiving hopper of the cyclone battery during periods of long-term operation of all furnaces in the optimal mode.

At the time of unloading the bunker, the dust temperature reaches 200 ℃, respectively, for more convenient transportation, the dust must be cooled on a specially prepared site, not allowing it to get wet. The selected dust in sealed containers is transported to the laboratory for research on flotation separation.
The first stage is to make a rough cleaning of the dust from the largest particles (large particles of quartz, wood and coal) that randomly found themselves in the selected samples. Dry screening on vibrating screens is used to separate these particles. The mesh size of the sieve is 1 mm.

The silicate and carbon phases of the dust of cyclones of silicon production are separately demanded products. The cost depends on the degree of purity, structure and particle size distribution of the particles. The particle size distribution of cyclone dust is shown in Figure 1.

![Figure 1. Particle size distribution of cyclone dust.](image)

Analysis of particle size distribution shows that cyclone dust particles have sizes from 0.1 to 200 microns. Both carbon and silicate particles of these sizes can be a valuable product with a fairly wide range of applications.

Various methods can be used to separate silicate and carbon phases from cyclone dust - sedimentation, dry separation, calcination, flotation. Sedimentation allows only the largest particles to be separated and is used only as a preparatory stage. Dry separation allows some separation to be obtained, but the recovery remains extremely low. Calcining the dust of cyclones in furnaces of various designs is extremely energy-consuming and will only produce a silicate phase. Silicon dioxide and carbon have pronounced differences in wettability, which indicates the effectiveness of the flotation separation method.

Particles of carbon are hydrophobic, particles of silicon dioxide are hydrophilic. There are flotation reagents used to enhance the specified properties. However, there is a persistent opinion in the literature that particles with a particle size less than 0.2 mm do not lend themselves to efficient flotation. Indeed, flotation of chalk-dispersed ones has a number of features.

Hydrophilic microparticles are subject to mechanical transfer into the foam layer. To suppress this effect, aeration of the pulp is necessary, in which the size of the bubbles will not exceed the size of the particles in the pulp. Flotation by microbubbles with the formation of bubble fog leads to the formation of bubble-particle flotation complexes, which significantly reduce the likelihood of the transport of hydrophilic particles into the foam layer.

Capillary forces are superior to gravitational forces even in the case of hydrophilic microparticles. To artificially increase the gravitational forces, a special circulation of the pulp is organized in the working chamber of the flotation machine, which contributes to the return of hydrophilic particles to the pulp.
3. Results of studies of the effect of the height of the foam layer on the concentration of the foaming agent, the dependence of the quality and quantity of output products on the time and mode of flotation

Microparticles tend to form stable heterogeneous conglomerates. As a result of the action of electrochemical forces, particles are formed, consisting simultaneously of silicon dioxide and carbon. Dissimilar particles can both be carried out into the foam product and remain in the chamber, reducing the quality of the concentrates. To solve this problem, pulp conditioning is used using sonochemical units, which facilitates the separation of a large number of conglomerates.

Hydrophilic microparticles do not have sufficient weight to "fall out" from the foam layer. In order for hydrophilic particles not to be retained in the foam layer, it is necessary to maintain a sufficiently thick layer of mobile and watered foam, then hydrophilic particles will be washed out of the foam layer through the interbubble channels. The leaching process can be intensified by organizing irrigation of the surface of the foam layer.

Based on the above features, the following technology of flotation separation of silicate and carbon phases of dust from cyclones of silicon production was developed. Figure 2 shows a block diagram of the technology.

![Figure 2. Block diagram of the technology of flotation separation of silicate and carbon phases of cyclone dust.](image)

At the stage of repulpation, the dust of cyclones is mixed with water in the required ratio and sonochemical separation of conglomerates occurs. At the stage of sedimentation, a phase with a size of more than 80 microns is separated, which is not of interest in the composition of the flotation output products.

For the flotation separation of cyclone dust, a pneumohydraulic flotation machine with an ejection aerator is used, which additionally produces sound processing of the pulp and generates bubbles up to 50-70 nm in size. During the experiments, the following flotation reagents were used:

- Pine oil - foaming agent;
- Kerosene – carbon collector;
- Liquid glass – silicon dioxide depressor.

The choice of reagents is due to their low cost and wide availability without sacrificing efficiency. The flotation time did not exceed one hour. Samples taken during the experiments were dried in an oven at 60 °C and analyzed by SEM, XRD, XRD, GOST 23581.9-79.

One of the most important indicators of the flotation kinetics is the quality of froth and chamber products depending on the flotation time. This dependence is shown in Figure 3.
The graph shows that the main part of carbon is extracted in the first 20 minutes of the experiment, further the carbon extraction slows down. This fact can be caused by the fact that the most characteristic carbon particles quickly enough fix on the bubbles and turn into foam, particles that are less prone to flotation due to their structure are removed much more slowly. The quality of the froth product remains stable in the first 30 minutes of flotation and deteriorates further. This fact can be caused by the fact that in the second half of the experiment, particles begin to float, which are heterogeneous conglomerates of carbon and silicon dioxide, the presence of which in the dust of cyclones was confirmed by scanning electron microscopy. In addition to the carbon content, the graph shows an integral curve showing the fraction of the recovered foam product (in terms of dry). There is a clear relationship between the recovery of the foam product and the reduction in the amount of carbon in the chamber product.

An important condition for ensuring a high degree of separation of microsized media is the maintenance of a foam layer with a set of the following qualities:

- The thickness of the foam layer is not less than 70 mm - a large contribution to the separation of media is the separation in the foam layer, which can proceed rather slowly.
- Foam must be mobile (not rigid) - for separation in the foam layer, a prerequisite is the presence of a sufficient interbubble space, through which hydrophilic particles leave the foam, returning to the cell of the cell;
- Foam should consist of small bubbles of close size - this condition is necessary to maintain a high foam layer since bubbles of similar size are much less prone to coalescence.

The height of the foam layer has a great influence on the flotation process [14-17]. The height and structure of the foam depends on many factors such as temperature and pH + slurry, aeration rate, and cell design. However, the simplest way to control the height of the foam layer is to maintain the required concentration of the foaming agent in the slurry. Figure 4 shows the measured foam thickness. Measurements were made before the start of flotation using a tape measure through the

![Figure 3. Dependence of carbon content in products on flotation time.](image-url)
transparent wall of the flotation machine. The foaming agent was added in steps, the other conditions remained unchanged.

![Dependence of foam layer height on foaming agent concentration](image)

**Figure 4.** Dependence of foam layer height on the concentration of the foaming agent.

The dependence shown in Figure 4 cannot be considered as universal, however, some conclusions can be drawn from it. Up to a certain concentration (in this case, up to 20 mg/l), the foaming agent does not accumulate at the air-liquid interface in an amount sufficient for the formation of stable bubbles on the surface and the growth of the foam layer. After a further increase in concentration (more than 20 mg/l in Figure 3), a rapid increase in the thickness of the foam layer occurs. In a certain range, the foam layer remains maximum (in the measured case, 40-70 mg/l). This concentration range not only allows achieving the highest foam layer, but also in this range the foam remains sufficiently mobile and watered, which contributes to effective separation in the foam layer.

In addition to the height and quality of the foam, the concentration of the collector (in this case, kerosene) has a great influence on the process of flotation of dust from cyclones of silicon production. The dependence of the recovery and quality of the foam product on the collector concentration is shown in Figure 5.

The graph shows that the most carbon-rich foam product is obtained without the addition of a collector. When a small amount of collector is added, a moderate drop in the quality of the foam product occurs (the carbon content is reduced to 95%) and the amount of recovered foam product more than doubles. A further increase in the collector concentration leads to a significant drop in the quality of the carbon concentrate (up to 90%) and dramatically increases the recovery. After a certain value of the collector concentration, the quality of the foam product ceases to decrease and the recovery increases. This fact is of great practical importance - to obtain the purest carbon concentrate, large concentrations of the collector cannot be used, since it "pulls" the particles of the chamber product behind it. This flotation mode is used for cleaning the foam product of the first stage of flotation. For cleaning (control flotation) of the chamber product of the first stage of flotation, it is necessary to use a higher concentration of the collector - this will lead to a better cleaning of the silicon dioxide concentrate from carbon.
It is worth noting the fact that when using hydrocarbon flotation reagents (kerosene, alcohols, etc.), it is necessary to take into account the possible contamination of both foam and chamber products by reagents.

![Dependence of FP recovery and quality on collector concentration](image)

**Figure 5.** Dependence of the foam product recovery and quality on collector concentration.

### 4. Conclusion

In the course of the study, the main features of the flotation separation of the silicate and carbon phases of cyclone dust were determined. Technical solutions are proposed that allow efficient separation in spite of the identified features.

A method of pulp conditioning has been developed, which increases the efficiency of flotation and, as a consequence, the quality of the output products.

The dependences of the height of the foam layer on the concentration of the foaming agent, the dependence of the quality and quantity of the output products on the time and mode of flotation are plotted.

The studies carried out have shown that the optimal processing of metallurgical production wastes makes it possible to obtain new technological materials that are not inferior to natural materials in their physicochemical properties. The combination of exceptional thermophysical, mechanical and physicochemical properties of nanosilica and carbon particles makes them unique materials for many branches of technology and predetermines such main applications as materials for modifying and activating flux compositions in metallurgy: modifiers for obtaining nanostructured ferrous metals and alloys, innovative silumins and special-purpose parts for mechanical engineering.

A further direction of research is to find new regularities of the kinetics of cyclone dust flotation, to construct and study the kinetics of flotation in three stages, both in discrete and continuous modes, as well as to develop technologies for using the products obtained for modifying various materials.

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