Impact of dust emissions from the silicon production on working conditions

M S Leonova and S S Timofeeva
Irkutsk National Research Technical University, Russia
E-mail: leonova@istu.edu

Abstract. Metallurgical enterprises are one of the largest sources of dust emissions. Dust is the main air pollutant in the working area and is formed in all areas where the metal production process is carried out. Thus, up to 900 kg of dust is formed in the production of 1 ton of silicon. Inhalation of such dust by workers of the foundry can contribute to the development of a number of dangerous respiratory diseases. Therefore, the aim of this paper was to study the dust waste of the silicon production and to analyze the working conditions of employees of the given enterprise in order to develop measures to reduce the dust load and improve the working conditions. The article also presents the results of studies of the particle size distribution of dust emissions in the silicon production. Using the X-ray phase analysis method, it was shown that the dust of the silicon production mainly consisted of amorphous silica, as well as silicon and carborundum. According to the results of the chemical analysis, it was found that this type of waste contained on average 86% of the valuable SiO$_2$ component. The particle-size analysis of the composition of gas cleaning dust from the silicon production showed that there were particles in the dust ranging in size from 0.1 to 600 µm. Most particles had a size of 50.00 + 100.00 µm. Particles of this size are easily inhaled by the operating personnel and quickly penetrate into the lungs and affect the lung tissue. During the assessment of the working conditions of the silicon enterprise by this factor, it has been found that all workplaces of the electrothermal department have hazardous conditions and correspond to the class of working conditions 3.2, and the allowable work period under these conditions is 6 years. The analysis of the above data shows that gas cleaning dust of the silicon production contains a significant amount of the valuable SiO$_2$ component, and the volumes formed allow this material to be used as a silica-containing raw material. Therefore, in order to effectively solve environmental problems and improve the working conditions of silicon production workers, it is necessary to develop innovative technologies for recycling fine silica-containing waste and other methods for their disposal.

1. Introduction
Modern metallurgical production is accompanied by the formation of a significant amount of dust fumes, which have a negative impact on the health and working ability of working personnel, contribute to the rapid deterioration of equipment of these enterprises, since most often the amount of dust in the working area air exceeds the level of MAC [1-3]. Also, hundreds of tons of dust emitted into the atmosphere harm the environment of nearby enterprises. Therefore, the urgent task is to develop comprehensive measures to improve working conditions and minimize environmental pollution [4].
Dust (aerosol) is the main air pollutant in the working area and is formed in all areas where the metal production process is carried out.

Thus, in the silicon production, dust is formed during crushing, loading, sorting, batch top layer settling, batch transporting. Also, the carbonothermal smelting of silicon itself is accompanied by the release of a significant amount of dust emissions. Just one ton of smelted silicon may account for as much as 900 kg of dust emissions [5].

Inhalation of such dust by workers in the foundry may contribute to the development of tuberculosis, pneumonia, and lung cancer [6,7]. There is also a group occupational lung diseases that occur during prolonged inhalation of dust - pneumoconiosis. This disease, depending on the type of dust impact, is divided into the following groups: silicosis, silicatosis, heavy-metal coniosis, carboconiosis, pneumoconiosis from mixed and organic dust [8,9]. Silicosis is one of the severe subtypes of pneumoconiosis and is the result of inhalation of dust containing free silicon dioxide under production conditions.

This dust getting into the respiratory tract dissolves slowly, since it contains a significant amount of SiO$_2$, thereby contributing to the progression of silicosis even after the cessation of work. Silicosis develops only after several years of dust inhalation [10].

In addition, inhaled dust particles are transported both to the cardiovascular system and to the heart, causing cardiac arrhythmia and a decrease in the heart muscle capacity and shortening the life span. It has also been proven that a number of mutagenic and carcinogenic chemicals contained in dust significantly affect human reproduction [11].

Presumably, the degree of negative effects on the human body is determined by such factors as the chemical composition of dust, the size of its particles and the ability to adsorb. Dust formed in mechanical processes has a particle size of up to 50 µm, in combustion processes - up to 70 µm, in chemical and thermal processes - up to 3 µm [12].

Also, the dust particle size determines the nature of its distribution in atmospheric conditions. Coarse dust has a size of more than 100 µm and settles at small distances from the source of pollution, fine (medium) dust has a size of more than 10 µm, spreads over considerable distances and accumulates slowly, and extra fine dust has a size of less than 10 µm, spreads rapidly and almost does not precipitate. The ore-smelting furnace in the process of electric smelting of silicon forms up to 1,000,000 nm$^3$/h of exhaust gases containing 1.5-2.0 g/nm$^3$ of dust [5].

Thus, the aim of this paper was to study the dust waste of the silicon production and to analyze the working conditions of employees of the given enterprise in order to develop measures to reduce the dust load and improve the working conditions.

2. Materials and methods

To determine the phase composition of dust, we performed an X-ray phase analysis of this material using a DRON-3.0 diffractometer (Russia) (Figure 1).

Figure 1 shows that the dust mainly consists of amorphous silica, as well as silicon and carborundum. Other impurities that were detected by XRF were not recorded on this X-ray due to their low content in the samples [5].

Also, according to the results of the chemical analysis, which are listed in Table 1, dust from the silicon production can be considered a promising raw material for the production of silicon [5,13].

To determine the range of particle size, we calculated the dependence of the distribution of gas cleaning dust particles from the silicon production by grain size (Figure 2).

We have conducted studies of the particle-size distribution of gas cleaning dust from the silicon production using a particle analyzer FRITSCH (Germany), which are presented in Table 2 [5].

The curve in this chart shows that there are particles in the dust ranging in size from 0.1 to 600 µm. Most particles had a size of 50.00 ± 100.00 µm [5]. Particles of this size are easily inhaled by the operating personnel and quickly settle in the lungs and affect the lung tissue [13, 14].
Table 1. Chemical composition of gas cleaning dust of the silicon production.

| Components | Content, % wt. |
|------------|---------------|
| SiO₂       | 86.3          |
| Al₂O₃      | 0.37          |
| Fe₂O₃      | 0.30          |
| CaO        | 1.4           |
| MgO        | 1.20          |
| C₄₆      | 5.8           |
| Na₃O       | 0.07          |
| SO₃        | 0.14          |
| P₂O₅       | 0.12          |
| K₂O        | 0.28          |
| TiO₂       | 0.02          |
| SiC        | 4.15          |

Table 2. Particle-size distribution of gas cleaning dust.

| Grain-size category, µm | Content, % |
|-------------------------|------------|
| -0.10 + 1.00            | 2          |
| -1.00 + 5.00            | 5.74       |
| -5.00 + 10.00           | 0.66       |
| -10.00 + 20.00          | 6.82       |
| -20.00 + 30.00          | 13.95      |
| -30.00 + 40.00          | 12.74      |
| -40.00 + 50.00          | 9.53       |
| -50.00 + 100.00         | 21.23      |
| -100.00 + 150.00        | 8.84       |
| -150.00 + 200.00        | 6.33       |
| -200.00 + 250.00        | 4.87       |
| -250.00 + 300.00        | 3.26       |
| -300.00 + 400.00        | 3.20       |
| -400.00 + 500.00        | 3.20       |
| -500.0 +600.00          | 0.75       |
| +600.00                 | 0.08       |
3. Results of the study and their analysis

In order to analyze and evaluate the working conditions of the silicon production workers, it is necessary to calculate the probability of occupational diseases, using an index to assess the degree of impact of strongly fibrogenic aerosols - SFA - on the respiratory organs using the example of the employees of the electrothermal department of Kremny CJSC.

An additional index of assessing the degree of SFA impact on the respiratory organs of the workers is the dust load (DL) [15].

DL is calculated by the formula 1, based on the SFA shift-average concentrations in the air of the working area, volume of pulmonary ventilation, which in turn depends on the intensity of labor and the duration of interaction with dust:

\[ DL = CNTQ \]

where \( C \) is the actual shift-average dust concentration in the breathing zone of a worker, \( mg/m^3 \); \( N \) is the number of shifts in a calendar year; \( T \) is the number of years in contact with SFA; \( Q \) is the volume of pulmonary ventilation per shift, \( m^3 \)[15].

Thus, let us calculate DL for 7 years of work as a smelter in the silicon production in the conditions of exposure to industrial dust containing 86% of SiO\(_2\).

According to production data, the daily average dust concentration (DAC) at Kremny CJSC is 8.33 mg/m\(^3\); category of work - III (the volume of pulmonary ventilation is 10 m\(^3\)); the shift-average MAC of this dust is 2 mg/m\(^3\); the average number of shifts per year is 228.

Accordingly: \( DL = 8.33 \text{ mg/m}^3 \cdot 228 \text{ shifts} \cdot 7 \text{ years} \cdot 10 \text{ m}^3 = 132,947.8 \text{ mg} \).

Also using the formula 2 we will determine the control dust load (CDL) for the same period of work:

\[ CDL = MAC_{sa} \cdot N \cdot T \cdot Q, \]

where \( MAC_{sa} \) - the maximum allowable shift-average concentration of dust, \( mg/m^3 \) - 2 mg/m\(^3\); \( N \) is the number of shifts in a calendar year - 228; \( T \) is the number of years in contact with SFA - 7; \( Q \) is the volume of pulmonary ventilation per shift, \( m^3 \) - 10.

Accordingly: \( CDL = 2 \cdot 228 \cdot 7 \cdot 10 = 31,920 \text{ mg} \).

Next, we will calculate the excess of CDL using the formula (3):

Excess of
Accordingly: excess of $\text{CDL} = 132,947.8 / 31,920 = 4.2$. That is, the actual $\text{DL}$ exceeds $\text{CDL}$ during the same period of work by 4.2 times.

Let us determine CDL for the average work period, which is assumed to be 25 years, using the formula 4:

$$\text{CDL}_{25} = 2 \cdot 228 \cdot 10 \cdot 25 = 114,000 \text{ mg}. \quad (4)$$

Next, we will determine the allowable work period in these conditions using the formula 5:

$$T_i = \frac{\text{CDL}_{25}}{\text{CNQ}}, \quad (5)$$

where $T_i$ is the allowable work period in these conditions; $\text{CDL}_{25}$ is the control dust load for 25 years of work in compliance with MAC; $C$ is the actual shift-average dust concentration; $N$ is the number of shifts in a calendar year; $Q$ is the volume of pulmonary ventilation per shift [9].

Therefore, the allowable work period in these conditions is 6 years.

In the analysis of the working conditions of the silicon enterprise by this factor, it has been found that all workplaces of the electrothermal department have hazardous conditions and correspond to the class of working conditions 3.2 [15].

Therefore, the issues of assessing and forecasting occupational and environmental risks, the development of measures to minimize them, to ensure safe working conditions for workers in the silicon production, to reduce the environmental burden, and thus to preserve the life and health of citizens are not fully resolved [15].

The analysis of the above data shows that gas cleaning dust of the silicon production contains a significant amount of the valuable SiO$_2$ component, and the volumes formed allow this material to be used as a silica-containing raw material. Therefore, in order to effectively solve environmental problems and improve the working conditions of silicon production workers, it is necessary to develop innovative technologies for recycling fine silica-containing waste and other methods for its disposal [5].

References
[1] Mann D A 2014 The effects of utilizing silica fume in portland cement pervious concrete Masters Abstracts International 53-04 98
[2] Inyang H I, Bae S 2006 Impacts of dust on environmental systems and human health J Hazard Mater 132 v–vi
[3] Rappaport S M, Goldberg M, Susi P, Herrick R F 2003 Excessive exposure to silica in the US construction industry Ann. Occup. Hyg Mar 47(2) pp 111–122
[4] ILO 1993 Encyclopedia of occupational health and safety (Geneva:“Silica”) 2 pp 2023–2043
[5] Nemchinova N V, Leonova M S, Tyturin A A, Bel’skii S S 2019 Optimizing the Charge Pelletizing Parameters for Silicon Smelting Based on Technogenic Materials Metallurgist 63(1-2) pp 115–122.
[6] Murzinov V L, Manokhin V Y and Ivanova I A 2011 A model to identify the process of dust formation in the working area of the foundry Polythematic network electronic scientific journal of the Kuban State Agrarian University 74(10) pp 1–12
[7] Azari M R, Rokni M, Salehpour S, Mehrabi Y, Jafari M J, Moaddeli A N, Movahedi M, Ramezankhani A, Hatami H, Mosavion M A, Ramazani B 2009 Risk assessment of workers exposed to crystalline silica aerosols in the east zone of Tehran Tanaffos 8 pp 43–50
[8] Lakhman O L, Kalinina O L, Zobnin Y V, Sedov S K 2013 Problems of diagnosing the initial form of occupational fluorosis in workers of modern aluminum production Siberian Medical Journal 6 pp 137–140
[9] Mamuya S H D, Bratveit M, Mwaiselage J, Mashalla Y J S and Bente E 2015 High Exposure to Respirable Dust and Quartz in a Labour-intensive Coal Mine in Tanzania pp 197–204
[10] Mannetje A, Steenland K, Attfield M, Boffetta P, Checkoway H, DeKlerk N, Koskela R S 2002 Exposure-response analysis and risk assessment for silica and silicosis mortality in a pooled analysis of six cohorts *Occup Environ Med* **59** pp 723–728

[11] Bhagia L J 2012 Non-occupational exposure to silica dust *Indian J Occup Environ Med* **16** (3) pp 95–100

[12] Abderrahim Nem-mar, Marc F Hoylaerts, Peter H M Hoet, Benoit Nemery 2004 Possible mechanisms of the cardiovascular effects of inhaled particles: systemic translocation and prothrombotic effects *Toxicology Letters* **149**(1-3) pp 243–253

[13] Kondratyev V V 2010 *Methods of collection and description of the dust phase in the silicon production: monograph* (Irkutsk: Publishing house ISTU) p 77

[14] Gift J S, Faust R A 1997 Noncancer inhalation toxicology of crystalline silica: Exposure-response assessment *J Expo Anal Environ Epidemiol* **7** pp 345–358

[15] Timofeeva S S, Timofeev S S 2014 Assessment of retrospective occupational risks at aluminum enterprises of the Irkutsk Region *Bulletin of ISTU* **10** (93) pp 114–119

[16] Martin S C, Larivière C 2014 Community health risk assessment of primary aluminum smelter emissions *J Occup Environ Med* **56** pp 33–39