Dust load in silicon production and occupational risks

M S Leonova, S S Timofeeva, M A Murzin
Industrial Ecology and Life Safety Department, Irkutsk National Research Technical University, 83, Lermontov Str., Irkutsk 664074, Russia

E-mail: leonova@istu.edu

Abstract. The aim of this paper was to study the characteristics of dust generated in technological processes in the production of silicon in the Irkutsk Region, as well as to assess dust load and occupational risks of the shop workers. Using chemical and X-ray phase analysis methods, as well as electron microscopy, it was shown that silicon dust contains more than 80% of silicon dioxide, which is a source of increased hazard for the workers of the enterprise. Also, using the scoring method, the questionnaire method, and the method of assessing the individual occupational risk level, it was established that the individual occupational risks of the studied occupations range from 1.1 \times 10^{-3} to 3.3 \times 10^{-3}. The increased concentration of finely dispersed man-made silicon production waste confirms the need to take organizational and technical measures to reduce the dust load, including the creation of economic conditions for pelletizing the batch.

1. Introduction
The widespread use of crystalline silicon and its alloys in the aluminum, chemical, aviation and automotive industries has led to the construction of powerful and technically advanced facilities for the electrothermal production of crystalline silicon in various regions of Russia. Such industrial facilities have been created and successfully operate in Eastern Siberia. However, Kremny CJSC, the only refined silicon plant in Russia, is located in the territory of the Irkutsk Region [1-3].

This enterprise produces silicon in three-phase ore-smelting furnaces with a capacity of 16.5 MV·A and 25 MV·A [4] from quartzite mined at the Cheremshansk quartzite mine, which is part of the enterprise. According to production data, the production volume of Kremny CJSC averages from 36 to 38 thousand tons per year.

A distinctive feature of the silicon production is a high level of dust content in the air of the working area. Sources of dust in the silicon production are the processes of crushing, loading, sorting, settling, and transporting the batch, as well as the carbothermal smelting process. One ton of smelted silicon accounts for 900 kg of dust emissions [5].

Under production conditions, dust enters the human body through the respiratory tract and accumulates in the lungs. The clinical picture of dust diseases is characterized by damage to the lung tissue or respiratory tract with the development of either pneumosclerosis or chronic bronchitis or bronchial asthma, as well as various combinations of these forms [6,7]. Pneumoconiosis occurs mainly when exposed to dust of various minerals, including silica and silicates (kaolin, talc, asbestos, cement). Depending on the type of dust [8] that caused the development of pneumoconiosis, there are also various types of this disease. For instance, silicosis refers to the form of pneumoconiosis caused by exposure to silicon dioxide, silicatosis - the effects of various silicates (in particular, kaolin -...
kaolinosis, talc - talcosis, asbestos - asbestosis, etc.), siderose - iron-containing dust, and mixed forms of pneumoconiosis are referred to according to the dust composition. For example, anthracosilicosis, siderosilicosis, and so on [9].

The combination of pneumoconiosis with pulmonary tuberculosis is referred to as coniotuberculosis; however, depending on the type of dust, there are silicotuberculosis, anthracotuberculosis, etc. The most common and most severe form of pneumoconiosis is silicosis. It is characterized by sclerotic (connective) degeneration of lung tissue, accompanied by the formation of nodules in the lungs. Pulmonary emphysema is also characteristic of silicosis. Often with silicosis, an enlarged heart is diagnosed, especially in acute stages of the disease. Typical silicotic nodules in rare cases can be found in the kidneys, bone marrow of tubular bones, liver and spleen [10-12]. In case of silicotuberculosis, the changes largely depend on the shape and predominance of the silicotic or tuberculous process. Tuberculosis-specific changes are usually localized in the apices of the lungs and in the subclavian regions, while silicotic changes are located in the middle and lower regions of the lungs. The degree of damage depends on the number of years of a worker in profession and individual characteristics [13-15].

In terms of disease progression, there are the following forms of pneumoconiosis: rapidly progressive; slowly progressive; late; regressive. Rapidly progressive stage I pneumoconiosis can be detected 3-5 years after the start of work in contact with dust, the progress of the pneumoconiotic process, i.e. transition of pneumoconiosis to stage II, is observed in 2-3 years. This form of pneumoconiosis, in particular, includes the so-called acute silicosis, which is essentially a rapidly progressive form of silicosis [16,17].

Slowly progressive forms of pneumoconiosis usually develop 10-15 years after the start of work in contact with dust, and the transition from stage I to stage II of the disease lasts at least 5-10 years. Pneumoconiosis developing several years after a worker has stopped working in contact with dust is usually called late [18,19].

The aim of the paper was to study the characteristics of dust generated in technological processes of the silicon production in the Irkutsk Region, as well as to assess dust load and occupational risks of the shop workers.

2. Materials and methods
The object of the study was gas cleaning dust of the silicon production, which is present in suspension in the air of the working area. It is known that the ore-smelting furnace in the process of electric smelting forms up to 1.000.000 nm/h of exhaust gases containing 1.5-2.0 g/nm³ of dust [5]. The gas phase is represented, %, on average, respectively: N₂ – 78; O₂ – 20; CO₂ – 1-2; CO – 0-1 [5].

According to production data, the dust of Kremny CJSC is represented on average by 86% of silicon dioxide, Table 1 (results of XRF performed using AARL–9900 instrument (USA) and chemical gravimetric analysis); also there were studies performed using scanning microscopy (Figure 1).

Figure 1. Electronic image of a fine fraction particle of man-made raw materials produced by Kremny CJSC: (1 - spheroidized SiO₂ particles; 2 - carbon inclusions)
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 2).

Figure 2. X-ray of a sample of gas cleaning dust of the silicon production.

Figure 2 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].

When studying the chemical composition of the dust, it has been established that it contains more than 80% of silicon dioxide and is a source of increased hazard for the shop workers [5].

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           |
| C₆₆        | 5.8            |
| Na₂O       | 0.07           |
| SO₃        | 0.14           |
| P₂O₅       | 0.12           |
| K₂O        | 0.28           |
| TiO₂       | 0.02           |
| SiC        | 4.15           |

At the enterprise under consideration, we thoroughly studied the staff schedule of main shops and measured the dust factor of the production environment. The actual values of the production environment parameters were measured using the equipment of the East-Siberian Shared Use Center “Technosphere Safety”. In the process, we used IKP - 5 dust meter designed to measure the mass concentration of dust and its fine fraction in the air environment while monitoring the excess of the maximum allowable concentration in the air of the working area with a relative error of ±20% [20].

For the main occupations of the enterprise under study, dust load on personnel and occupational risks were calculated according to the three methods recommended by GOST 12.0.230.5 - 2018. We
chose the following methods: scoring method; questionnaire method; method of assessing the individual occupational risk level.

3. Results of the study and their analysis

The production of crystalline silicon is a complex multistage technological process based on the reduction of silicon dioxide with carbon-containing materials, which includes a series of sequential operations - the preparation of batch materials, their thermochemical processing, and the production of crystalline silicon itself [4].

The leading hazardous occupational factor characterizing the working conditions in the production of crystalline silicon is a high level of the dust content in the air of the working area.

We measured the dust content at the workplaces of the main occupations and obtained the following results.

During the technological operations of unloading wagons, transferring raw materials in warehouses, crushing, transporting and dosing of the batch, batch makers are exposed to disintegration aerosols, the concentrations of which amount to 18.5±4.5 mg/m³, and the silicon dioxide content is 12.0%.

At the workplaces of smelters, when performing settling and casthouse work, the air in the working area is contaminated with condensation aerosols. The content of silicon dioxide in them varies between 10-70%, elemental crystalline silicon, respectively, from 89 to 87%, the concentrations are 11.3±2.1 and 7.6±2.30 mg/m³.

When checking and cleaning soot and ash from gas ducts, furnaces and gas cleaning equipment, chimneys of electrothermal furnaces, as well as loading soda into containers and cleaning sludge, cleaners are exposed to disintegration aerosols at a concentration of 15.7±3.1 mg/m³, consisting of 80% crystalline silicon and only 6.1% silicon dioxide.

Table 2 shows the calculated value of the safe work period for the main occupations in the silicon production.

Table 2. Safe work period for the silicon production personnel.

| Occupation   | Shift-average dust concentration, mg/m³ | Safe work period, years |
|--------------|----------------------------------------|-------------------------|
| Batch maker  | 18.5±4.5                               | 13.5                    |
| Smelter      | 11.3±2.1                                | 21.3                    |
| Cleaner      | 15.7±3.1                                | 16.3                    |

Calculations have shown that individual occupational risks of the occupations studied range from 1.1 10-3 to 3.3 10-3.

Thus, we can conclude that the dust load is a determining factor for occupational risks and it is necessary to take organizational and technical measures to reduce the dust load, including the creation of economic conditions for pelletizing of the batch.

References

[1] Sizyakov V M, Vlasov A A, and Bazhin V Yu 2016 Strategic objectives of the Russian metallurgical complex Nonferrous metals 1 32–38
[2] Hesse K and Freiheit H C 2008 Challenges of Solar Silicon Production Proc. of the Intern. Scientific Conf. Silicon for the Chemical and Solar Industry IX 61–67
[3] Yolkin K S 2014 Production of metallic silicon in Russia: the state and prospects Book of Reports of the 6th International Congress Nonferrous metals and minerals 180–182
[4] Popov S I 2004 Silicon metallurgy in three-phase ore-smelting furnaces (Irkutsk: Kremny CJSC) p 237
[5] Leonova M S 2017 Development of the technology for preparing the batch from man-made raw materials for the silicon production Candidate Degree Dissertation in Engineering Science (Irkutsk) 202 p
[6] Mannetje A, Steenland K, Attfield M, Boffetta P, Checkoway H, DeKlerk N and 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 59 723–728
[7] Lumens M E and Spee T 2001 Determinants of exposure to respirable quartz dust in the construction industry Ann Occup Hyg 45(7) 585–595
[8] Esswein E J, Breitenstein M, Snawder J, Kiefer M and Sieber W K 2013 Occupational exposures to respirable crystalline silica during hydraulic fracturing J Occup Environ Hyg 10 347–356
[9] World Health Organization Occupational and Environmental Health Team 2006 Elimination of Asbestos-Related Diseases (Geneva: World Health Organization) p 4
[10] Peeters P M, Perkins T N, Wouters E, Mossman B T and Reynaert N L 2013 Silica induces NLRP3 inflammasome activation in human lung epithelial cells Part Fibre Toxicol 10 3
[11] Zinchenko V A, Razumov V V and Gurevich E B 2002 Occupational chronic obstructive pulmonary disease (COPD) - a missing link in the classification of occupational lung diseases (critical review) Clinical aspects of occupational pathology: collection of research papers 15–18
[12] Rom W N and Markowitz S 2007 Environmental and Occupational Medicine (PA: Lippincott Williams & Wilkins) p 1904
[13] American Thoracic Society Committee of the Scientific Assembly on Environmental and Occupational Health 1997 Adverse effects of crystalline silica exposure Am J Respir Crit Care Med 155 761–768
[14] Mason R J, Murray J F, Nadel J A and Broaddus V C 2005 Murray and Nadel’s Textbook of Respiratory Medicine (PA: Elsevier Saunders) p 2609
[15] Mohammadyan M, Rokni M, Yosefinejad R 2013 Occupational exposure to respirable crystalline silica in the Iranian Mazandaran province industry workers Arh Hig Rada Toksikol 64 139–143
[16] Sirajuddin A and Kanne J P 2009 Occupational lung disease J Thorac Imaging 24(4) 310–320
[17] Stark P, Jacobson F and Shaffer K 1992 Standard imaging in silicosis and coal worker's pneumoconiosis Radiol Clin North Am 30(6) 1147–1154
[18] Navarro C, Mejia M, Gaxiola M, Mendoza F, Carrillo G and Selman M 2006 Hypersensitivity pneumonitis: a broader perspective Treat Respir Med 5(3) 167–179
[19] Kumar V, Abbas A K, Aster J C and Fausto N 2010 Robbins: Pathologic basis of disease (Philadelphia: Saunders Company) p 1464
[20] Timofeeva S S 2014 Methods and technologies for assessing production risks: practical course (Irkutsk: Publishing house ISTU) p 178