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Technologies, which allow to reduce an impact of metal silicon production on the environment

K S Yolkin¹, D K Yolkin² A D Kolosov³, N A Ivanov³ and M G Shtayger⁴
¹UC RUSAL, RUSAL Engineering Technology Centre, 40 Pogranichnikov street, Krasnoyarsk, 660111, Russia
²RUSAL, JS Company “Kremniy”, 26 Yuzhnaya street, Shelekhov, 666034, Russia
³Irkutsk National Research State Technical University, 83 Lermontov street, Irkutsk, 664074, Russia
⁴MC Mechel Steel, 1 Krasnoarmeysky street, Moscow, 125167, Russia

E-mail: karlinat@mail.ru

Abstract. It is shown that silicon carbide can be used as a reducing agent in the production of metallic silicon. The results of tests of silicon carbide are presented. The possibility of reducing the amount of furnace gases is shown. The calculated amount of decrease in the amount of waste furnace gases is confirmed by the test results.

1. Introduction
Organic-silicon compounds combine the best properties of silicates; on the basis of silicones, heat-resistant lubricating oils, liquid dielectrics, varnishes, enamels, rubbers, plastics, fiberglass, effective sorbents, catalysts are produced.

High purity silicon is a typical semiconductor and is widely used in modern electrical engineering, radio engineering and electronics. A special place is occupied by solar power on the basis of crystalline silicon, share of which increases significantly to obtain cheap electricity.

Modern technology of silicon production, used in world and domestic practice, is associated with a risk of negative impact on the environment, because in addition to the final product, other reaction products are formed, including dust from incomplete use of charge materials.

Metallic silicon is produced by high-temperature reduction of silica with the help of reducing agents in arc ore thermal electric furnaces. A feature of the industrial production of silicon is the use of silica-containing raw materials and carbonaceous reducing agents, characterized by a high content of useful components and a low content of slag-forming impurities, and therefore, silicon smelting reduction is practically a slag-free process [1]. The gases, released by smelting in ore-thermal furnaces, are characterized by the content of a large amount of fine dust. 94-96% of dust content is silicon dioxide [2]. As a result of using the furnace gases, which are entered to be cleaned, as sulfur-containing raw materials, sulfur compounds in the form of SO₂ are present in the these furnace gases, in addition, there are also nitrogen oxides.

The reduction of silicon occurs from the total reaction

\[ \text{SiO}_2 + 2\text{C} = \text{Si} + 2\text{CO} \] (1)

Modern theory considers that the recovery of silicon in ore-thermal furnaces occurs in two stages:
1 stage (low-temperature zone of the furnace) - formation of silicon carbide by the reaction

\[ \text{SiO}_2 + 3\text{C} = \text{SiC} + 2\text{CO} \] (2)

2nd stage (high-temperature zone of the furnace) - production of silicon by the reaction

\[ \text{SiO}_2 + 2\text{SiC} = 3\text{Si} + 2\text{CO} \] (3)

Considering the coefficients, total overall reaction has the following form:

\[ 3\text{SiO}_2 + 6\text{C} = 3\text{Si} + 6\text{CO} \] (4)

As can be seen from this reaction, amount of reaction gases formed by mass is twice that the amount of the final product. To reduce the negative impact on the environment was one of the main aims of this work.

If to compare the above mentioned reactions 1, 3, and 4, it can be seen that in the production of three moles of silicon in the first case, reactions 1, 4, six moles of CO are formed, as received the same amount of silicon by reaction 3, two moles of CO are formed. This relationship formed the basis for industrial tests on the use of silicon carbide in the production of technical silicon in powerful industrial electric furnaces according to the technology developed by the authors [2]. During the tests, assessment of the furnace productivity and quality of the smelted silicon was made, amount of waste furnace gases was measured, presence of contaminants in them, and comparison with the operation of the furnace on a typical charge for the production were made.

The tests were carried out on a 25 MVA furnace.

The furnace operation performances, in stages, are summarized in table 1, change in furnace operation, productivity, specific electricity consumption, which depends on the amount of used silicon carbide, are shown in figure 1.

| Table 1. Furnace operation performances with the use of silicon carbide materials. |
|---------------------------------------------------------------|
| **Consumption per 1 ton of silicon, t/t**                     |
| Typical charge                                               |
| Quartzite                                                    | 3.046 | 2.787 | 2.658 | 2.654 | 2.324 |
| Silicon carbide material                                     | -     | 0.323 | 0.409 | 0.508 | 0.627 |
| Electricity, mWh/t                                           | 16.28 | 16.200| 14.623| 14.164| 13.223|
| Productivity, t/day                                          | 29.40 | 30.96 | 34.47 | 35.35 | 37.96 |

During the tests, calculations of the amount of reaction gases, occurring in the silicon smelting reduction process, on typical and experimental charges were carried out (table 2).

| Table 2. The amount of occurring gases per 1 ton of silicon. |
|-------------------------------------------------------------|
| **gases** | **typical charge** | **replacement 10 % C** |
| CO        | 2414 nm³          | 1985 nm³             |
| CO₂       | 1134 nm³          | 803 nm³              |
| H₂O       | 3041 nm³          | 2079 nm³             |
| Total     | 6589 nm³          | 4867 nm³             |
Figure 1. Change of the furnace operation performances using silicon carbide materials.

During the tests, measurements of the amount and composition of gases, leaving the furnace, during the operation on a typical charge and in case of replacing a part of the reducing agent with silicon carbide materials. Changes in the number and types of contaminants in the composition of waste gases were estimated. All measurement results are summarized in table 3.

Table 3. Results of instrumental determination of the composition of gases and the amount of contaminants of the silicon furnace.

| Used charge | Typical charge | Charge with the use of SiC |
|-------------|----------------|---------------------------|
| Parameter   | Emission value | Emission value | Change in comparison with the typical one, % | Emission value | Change in comparison with the typical one, % |
| Gas volume, | 236625         | 214200     | -9.5 | 205600     | -13.1 |
| nm³/h       | 236625         | 214200     | -9.5 | 205600     | -13.1 |
| Dust, kg/h  | 1252.97        | 991.27     | -20.1 | 801.098    | -36    |
| kg/t Si     | 1019.5         | 678.95     | -20.1 | 549.3      | -36    |
| CO₂, kg/h   | 31.2           | 22.465     | -28.1 | 20.07      | -35.7  |
| kg/t Si     | 25.47          | 15.387     | -28.1 | 13.74      | -35.7  |
| NO, kg/h    | 64.6           | 29.16      | -55   | 9.5        | -64.5  |
| kg/t Si     | 52.6           | 19.975     | -55   | 6.51       | -64.5  |
| NO₂, kg/h   | 4.99           | 1.836      | -63   | 0.54       | -0.89  |
| kg/t Si     | 4.06           | 1.257      | -63   | 0.32       | -0.89  |
| SO₂, kg/h   | 5.66           | 5.32       | -6    | 1.7        | -70    |
| kg/t Si     | 4.6            | 3.6        | -6    | 1.15       | -70    |
Figure 2. Change in quantity of furnace gases.

Figure 3. Change in dust content of furnace gases.
The conducted studies showed high efficiency of silicon carbide materials application as a reducing agent in the production of metallic silicon. Efficiency was achieved due to increased productivity of the furnace, decrease in the consumption of raw materials and materials.

A significant ecological effect was achieved due to a decrease in the amount of waste gases and a decrease in the dust content of the gases. The composition of the gases also changes significantly, which leads to a reduction in the unfavorable environmental load in the area of the location of the enterprise.

2. Conclusions
1. The use of silicon carbide materials in the silicon reduction smelting increases the productivity of the furnace, reduces the consumption of process electricity in proportion to the amount of carbon replaced by silicon carbide.

2. Replacement of carbon with silicon carbide material in the composition of reducing agents reduces dust content, amount and composition of waste furnace gases, by reducing the amount of contaminants, which reduces the environmental load.

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Figure 4. Change in composition of furnace gases.
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