DOI: 10.18721/JCSTCS.13406
УДК 004.94

ANALYSIS OF THE STATE OF AUTOMATION OF MATERIAL FLOW CONTROL IN SILICON PRODUCTION

O.N. Masko, D.V. Gorlenkov

Saint-Petersburg Mining University,
St. Petersburg, Russian Federation

The problem of material flow control has a key significance in the silicon production since the proportional composition of furnace-charges (specific gravity, taking into account moisture) and current state of the furnace (slagging and etc.) essentially affect the yield and quality of the finished product, and the efficiency of the technological process as a whole. The relevance of the topic lies in the need to modernize and increase the level of transparency of production processes in the silicon industry. In this analytical review, the following tasks have been solved: the suitability of using automated material flow control systems in the silicon production has been proved; the bottlenecks of the process in terms of saving resources have been identified; the functionality of the automated material flows control system has been determined by means of examples of similar production; the method of control of emissions of valuable components has been put forward; the functional structure of the automated control system of the highest production level for the company "Silarus" has been proposed. This article examines the state of automated material control systems in the silicon production. The reasons for the introduction of such systems have been substantiated by the example of ferroalloy production. The general principles of the organization of automated systems of the factory operation of the largest foreign silicon enterprises, and their role in the accounting and management of material flows have been determined. A method for controlling the quality of microsilica capture has been proposed.

Keywords: metallurgical silicon, ore-smelting furnace, material flows control system, material balance, carbothermic reduction, MES system, microsilica.

Citation: Masko O.N., Gorlenkov D.V. Analysis of the state of automation of material flow control in silicon production. Computing, Telecommunications and Control, 2020, Vol. 13, No. 4, Pp. 66–77. DOI: 10.18721/JCSTCS.13406

АНАЛИЗ СОСТОЯНИЯ АВТОМАТИЗАЦИИ УПРАВЛЕНИЯ МАТЕРИАЛЬНЫМИ ПОТОКАМИ В ПРОИЗВОДСТВЕ КРЕМНИЯ

О.Н. Масько, Д.В. Горленков

Санкт-Петербургский горный университет,
Санкт-Петербург, Российская Федерация

Проблема управления материальными потоками имеет центральное значение в производстве кремния, поскольку пропорциональный состав компонентов загрузочного материала (в удельном весе с учетом влажности), а также текущее состояние самой печи (зашлакование, закварцевание печи и т. п.), существенно влияют на выход, качество готового продукта и на эффективность технологического процесса в целом. Актуальность темы заключается в необходимости модернизации и повышения уровня прозрачности производственных процессов в кремниевой промышленности. В данном аналитическом обзоре решены следующие задачи: обоснована целесообразность применения автоматизированных систем управления материальными потоками в производстве кремния; выявлены узкие места процесса карботермического восстановления кремния с точки зрения сбережения материальных и энергетических ресурсов; определена функциональность АСУ материальными потоками на примерах производств, подобных кремниевому; обоснован метод контроля выбросов ценных компонентов в процессе выплавки металлургического кремния и предложена функциональная структура АСУ верхнего производственного уровня для предприятия ООО «Силарус». Представлено состояние автоматизированных систем управления материальными потоками в производстве кремния в России и в мире. Обоснованы предпосылки и возможность внедрения подобных систем на примере ферросплавных производств. Определены общие принципы организации систем автоматизации верхнего уровня производства крупнейших зарубежных кремниевых предприятий, их роль и функциональные особенности в учете и управлении материальными потоками. Предложен метод контроля качества улавливания печной пыли.

Ключевые слова: металлургический кремний, руднотермическая печь, система управления материальными потоками, материальный баланс, карботермическое восстановление, MES-система, микросилика.

Ссылка при цитировании: Масько О.Н., Горленков Д.В. Анализ состояния автоматизации управления материальными потоками в производстве кремния // Computing, Telecommunications and Control. 2020. Vol. 13. No. 4. Pp. 66–77. DOI: 10.18721/JCSTCS.13406

Introduction

Silicon is a key raw material for a number of strategically important industrial sectors. Polycrystalline silicon, which is a raw material for solar energy and the semiconductor industry, is produced from metallurgical-grade silicon with a purity of up to 98–99 %. With the development of the metallurgical industry, the use of silicon of metallurgical grades as an alloying additive to special steel and aluminum alloys is growing.

In industry, metallurgical (technical) silicon is produced by reducing the SiO_2 melt with carbon at a temperature of about 1800 °C between carbon-graphite electrodes in ore-thermal furnaces (OTF) of the mine type. The production of crystalline silicon is accompanied by the following set of technological operations: preparation of the charge, melting it in OTF, casting of silicon and its subsequent grinding to remove slag inclusions.

Loading the charge into the OTF is one of the most difficult stages of carbothermic silicon reduction. The exact compliance with the proportional composition of the charge materials directly affects the electric mode of the furnace and, subsequently, the quality of the finished product.

The complexity of the loading process consists in the need to load large volumes of charge on a relatively small area of the grate (more than 50 tons per 70–80 m^2). It is at the stage of loading the furnace that deviations in the material balance appear. Ensuring a smooth, continuous lowering of materials into the furnace without stopping or breaking is one of the main tasks of the OTF management. The disruption of the process of charge material run-off complicates the stability of OTF operation [1].

Violation of the proportional composition of the charge also leads to an increase in the volume of dust emissions containing a significant amount of valuable silica, which can be effectively sold on the market. Microsilica emissions in low-efficiency production, where there are no gas cleaning plants, can reach 50 %. This dust is blown out by reaction gases, when it enters the furnace or at the time of their formation, and is carried to the grate, where it is diluted with air. All this leads to the useless combustion of hydrocarbons. In the presence of a gas cleaning system, the gas-dust mixture is captured by a gas collecting probe. Furnace dust also pollutes the environment, negatively affecting the technical and economic performance of the plant [2].

It is possible to solve the problems mentioned above by increasing the level of the process automation, including through the introduction of material flow management systems.

Control of the material flow movement

Accounting for the movement of charge and other auxiliary materials is one of the main tools for financial and technical management of production based on the calculation of the material balances of raw materials processing into a finished product.

The material balance is the main indicator of the work of the workshop and the enterprise as a whole, reflecting the degree of efficiency of the technological process. On the basis of the material balance, both the extraction and the loss of valuable components are calculated, the technology is analyzed, etc. It is obvious that a more accurate balance gives a more correct idea of the process, allows revealing the reserves of production.

In the process of measuring the mass concentrations of components involved in the technological process, measurement errors are inevitable. The combination of them leads to an incorrect assessment of the company's resources and generates financial risks.

Accurate information about the composition of the raw materials and the final product is crucial to reduce the possible losses associated with incorrect estimates of material stocks, as well as to quickly identify them.

Automated control of the material balance allows you to:

- strategically plan enterprise resources;
- record any changes in the composition and quantity of raw materials;
- identify unknown material losses;
- calculate and account for measurement errors;
- compare input and output flows for the billing period [3, 4].

Domestic practices of application of material flow management systems

In Russia, technical refined silicon is produced at a single plant: "RUSAL" JSC. The volume of its finished products is about 1 % of the world production. An analysis of the production of domestic silicon shows that the degree of automation of the process has low indicators. Only the data of the first level is used as regulated parameters, but there is no automation of the upper (shop) level, which seriously affects the quality of the finished product.

It is necessary to modernize the production of silicon, to solve the tasks of effective management through multi-level automated process control systems along with the introduction of high-tech equipment and implement closed-cycle technologies.

The lack of timely and adequate data on the concentrations of charge components, material reserves, and carbon consumption leads to the irrational use of raw materials and energy resources, as well as to forced production downtime.

The uncorrected material balance of carbon in the charge, the inaccuracies in its calculation lead to an increase in silicon monoxide emissions, which negatively affects the state of the environment and reduces the degree of silicon recovery. When creating new modern technologies, the experience of advanced domestic enterprises for the production of metallurgical silicon should be taken into account. New technologies should solve the problems of resource and energy conservation, as well as to improve the environmental situation in the region by reducing the emissions of microsilica into the atmosphere [5].

As a typical example of a material flow management system, due to the lack of data on such systems in the production of silicon, consider the automated system for accounting for material flows and calculating the material balance of the metallurgical shop of the Copper Plant of "Norilsk Nickel" JSC, developed by "Summa Technologies". The metallurgical shop of the Copper Plant is one of the most significant subsidiaries of "Norilsk Nickel" JSC. The task of automating the accounting of material flows and calculating the balance of metals is particularly acute here. The products of the metallurgical shop account for about a quarter of the company's total marketable products. Within the workshop, 72 products are

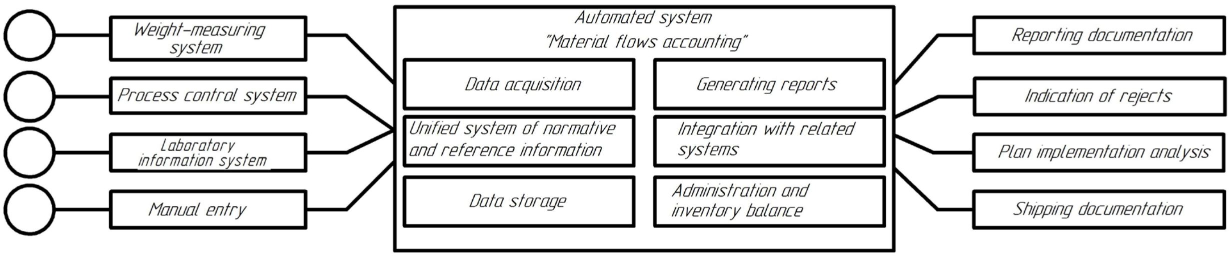

Fig. 1. Functional structure of the automated system "Accounting of material flows" of the metallurgical shopfloor of the Copper Plant

accounted for, each of which is analyzed for the amount and percentage of from 2 to 32 chemical elements, in total, more than 830 parameters are monitored.

The system allows you to track valuable components in the composition of materials for all stages of the workshop. The development of the system was accompanied by the introduction of automation of the products weighing operation.

The automated system for accounting for material flows and calculating the balance of metals provides more accurate control of the main technological parameters of the metallurgical shop of the Copper Plant, minimizes errors in the formation of documentation for products, provides timely reliable data for analyzing the quality of raw materials, optimizing the enrichment processes and increasing the recovery rate of precious metals [6].

"Norilsk Nickel" represents a multi-stage value chain of finished products from ore mining to metalworking. Continuous transformation of production, including digital, a huge number of interconnected objects makes it impossible to accurately quantify the effectiveness of a particular automated control system.

In the case of the balance of metals, it is possible to assess the efficiency of the integrated automated control system, covering all divisions of "Norilsk Nickel", including the system of the metallurgical shop of the Copper Plant under consideration:

- Data collection is 90 % automated, which minimizes the risks of misrepresentation of balance sheet data.
- Labor costs for collecting and forming balance sheets have been reduced by 70 %.

Material flows are not usually managed by a separate automated system. Automation of material flow management is carried out by implementing operational production management systems – systems of the MES class (manufacturing execution system), where accounting for material flows and reducing material balance are functions of only one of several system applications (modules).

To analyze the prospects of using MES systems to control the material flows of silicon production, we will consider ferroalloy production, which has a lot in common with enterprises that produce metallurgical silicon.

The main product of ferroalloy production is ferrosilicon. The process of smelting ferrosilicon is also based on the reduction of silicon from its dioxide in quartzite by carbon of coke and coal in an ore-thermal furnace and fusing it with iron of steel chips. In the production of ferrosilicon, the same problems occur as in the production of metallurgical silicon, namely, the influence of the charge composition on the electric mode of the furnace and the dust removal of valuable components, these disturbing factors can be eliminated by increasing the level of automation of production, including by implementing a MES solution.

The results of the implementation of the current MES class system, namely its module responsible for accounting for raw materials, are considered on the example of the "Aksu Ferroalloy Plant". The Enterprise Information System (EIS) is developed on the basis of the Wonderware software platform. It rep-

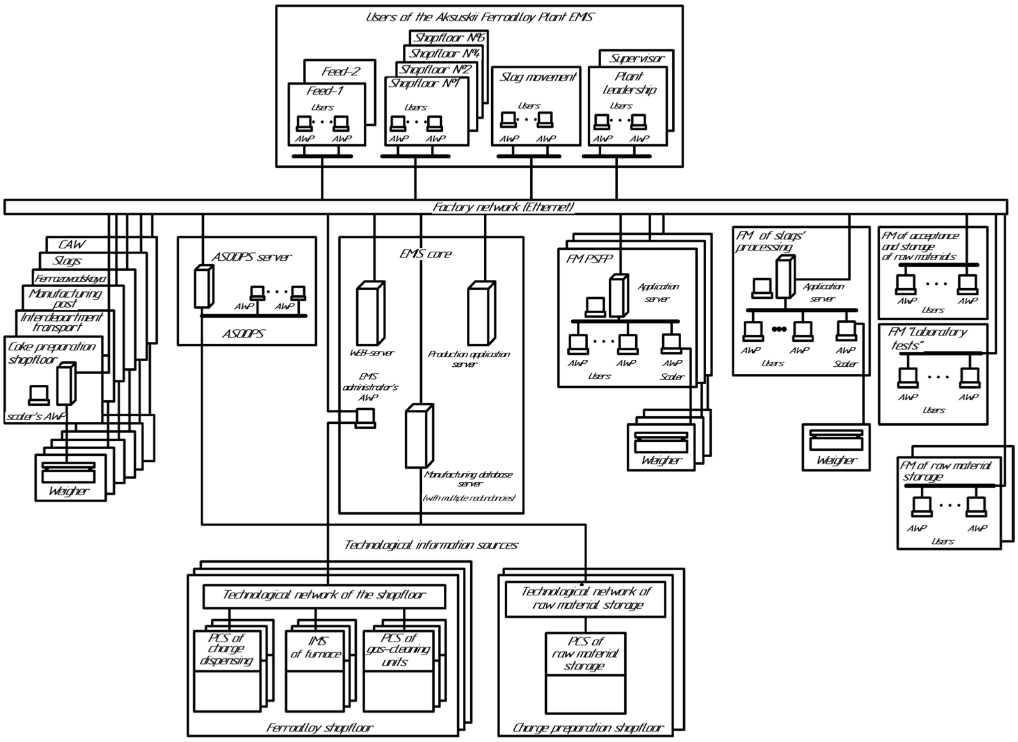

Fig. 2. Structure of EMIS of the Aksuskii Ferroalloy Plant:
CAW – central automobile weight room; FM PSFP – functional module of production, storage and shipment of finished products; IMS – information measurement system; awp – automation-equipped working place; ASODPS – automated system of operational dispatch control and power supply management

resents a single information space covering the main workshops and auxiliary divisions. This system was introduced in production in 2008 in order to reduce production costs by identifying the places and causes of production losses, inappropriate use of materials (including raw materials) and finished products.

The Automated System of Accounting and Control of material flows (ASCMF) is integrated into the plant's EIS and is a set of software and hardware tools for measuring, accounting for and controlling the movement of raw materials and finished products at the shop level and at the enterprise level.

Fig. 2 shows the detailed structure of the "Aksu Ferroalloy Plant" EIS, consisting of:

– core EIS;

– automated system of operational and dispatching control and management of power supply (ASODPS);

– functional modules;

– ASCMF.

The implementation of the system was carried out by stages in the form of functionally complete units of accounting for material flows (from the shipment of raw materials to the unloading of finished products).

As a result, the following qualitative improvements are identified:

• increased production efficiency by monitoring and analyzing the resources used and technological processes from the inside;

• an increase in the quality of the finished product (reduction of scrap, waste);

• compliance with the requirements of customers and supervisors by tracking the movement of the product from the raw material to the finished product.

With regard to the cost-effectiveness of the MES implementation, the following results were expected:
- reduced downtime of process equipment by 5 %;
- reduction of specific consumption of raw materials for the production of ferroalloys by 1 %;
- reduction of specific energy consumption for the production of ferroalloys by 2 % [7].

Main functions of MES systems for "Kuznetsk Ferroalloys" JSC:
- data collection and storage (DataCollection/Acquisition, DCA);

Collection of information from all automated process control systems and other related automated systems related to the course of the production process: the electric mode of operation of the furnace, the exact composition of the charge in specific gravity, the quality parameters of the finished product, etc.
- production process management (Process Management, PM);

Operational monitoring of the adjustment of the production process, either in automatic or automated (with the participation of the operator) mode. In any case, this function is based on an intelligent expert system that, based on the analysis of historical data on the parameters of the technological process and the resulting melt, selects the optimal composition of the charge, as well as the electric mode of the furnace.
- quality management (Quality Management, QM);

Manages laboratory studies of the parameters of the produced ferrosilicon, as well as provides analysis of the measured parameters in a close to real time mode.
- efficiency analysis (Performance Analysis, PA).

Generating reports on the actual results of production activities, comparing them with historical data and the expected commercial result. Formation and consolidation of the material balance for its transfer to the ERP system (enterprise resource planning).

In order to obtain reliable data, simultaneously with the introduction of MES at "Kuznetsk Ferroalloys" JSC, the existing automated process control system was upgraded. Measurement and control systems were put into operation to determine the humidity/icing of the charge components on the belt, as well as to measure the actual mass of the ferrosilicon melt. Control of the electric mode of the furnaces was also improved [8–10].

The successful implementation of the project significantly increased the profitability of the enterprise. Thus, from 2007 to 2012, the following positive results were achieved in the context of the global economic crisis:
– ferrosilicon smelting increased by 12 %;
– labor productivity increased by 42 %;
– number of highly qualified personnel increased by 10 %.

Foreign practices of application of material flow management systems in the silicon industry

The leader of silicon production today is China, with the production lines focused on silicon of the highest grades, including silicon for "solar energy". Approximately 40 % of the silicon market is occupied by Europe and the United States.

The major players in the silicon and polysilicon market are looking to expand the vertical integration of their businesses. Foreign enterprises are focused on the production of polycrystalline silicon used in the solar energy and semiconductor industries, which increases the value of the finished product and the profitability of production.

Due to the complexity of the production chain and the multi-stage process of raw material preparation, the level of automation, including top-level automation, is a single network covering all stages of production. Below are examples of the organization of operational management systems, including automated material flow management systems at enterprises that produce polysilicon.

For example, in 2004, in order to minimize production costs, the international company Wacker Polysilicon AG (Germany, USA) launched a group-wide program – Wacker Operating System (WOS) to increase productivity through the internal supply chain: from servicing and purchasing raw materials through production to packaging and shipping the finished product. Wacker has its own academy to train personnel for WOS maintenance [11–13].

In December 2006, TEC Silicon ASA (Norway/USA) installed an enterprise-wide MES system based on OSIsoft PI datahistorian. Its built-in intelligent forecast can increase the efficiency of the enterprise by 2 % or more [14].

The company SUPCON XinteEnergyCo. (China) won a contract to develop integrated solutions for a smart plant for the 36,000 tons per year polysilicon production base modernization project from XinteEnergyCompany in 2018. SUPCON will deliver a comprehensive intelligent solution for subsequent implementation, covering both the management of individual processes and the management of general enterprise information [15].

The analyzed foreign enterprises for the production of silicon followed the path of combining information systems that automate the activities of certain production units, without separating each division and technological process. These plants have fully integrated material flow control systems that process operational data in a single reporting format for the enterprise. This allows us to avoid disparate, poorly combined data and create an adequate analytical base for strategic resource planning [16, 17].

Based on the study of the possibilities of modernizing the process of material flow management in silicon production, using the example of the implemented automated system for accounting for material flows and calculating the material balance of the metallurgical shop of the Copper Plant, as well as the MES systems for ferroalloy production, it is possible to conclude that it is advisable to introduce an automated system for managing material flows at silicon production enterprises.

“Silarus” LLC

The platform for the implementation of this type of system is “Silarus” LLC, which is launching a new type of plant in the Sverdlovsk region. The main focus of the project is aimed at obtaining silicon of different grades with the associated recycling of related components, followed by their chemical transformation into high-quality commercial products.

To obtain high-purity silicon, it is necessary to pay special attention to improving the quality of the initial charge material, adjusting the technological parameters with high controllability and automation of the process, choosing the optimal type of carbon reducing agent, and improving the quality of graphite electrodes in ore-thermal furnaces.

It is also necessary to take into account the environmental safety of production and strive for effective capture of industrial emissions in the form of silicon dust and ash with their subsequent processing [19].

To address the above issues, “Silarus” SPA offers a number of new technical solutions for silicon production:

- It is planned to launch its own production of the main carbon reducing agent, charcoal, followed by the use of birch bark in the pharmaceutical industry. This solution will improve the quality of the reducing agent by controlling all stages of the technological process of coal production, as well as reduce the cost of the reducing agent.
- The use of chlorine-free technology for obtaining solar-quality silicon (high-temperature refining).
- Recycling of thermal energy generated in the process of carbothermic reduction of silicon.
- Implementation of an automated material flow management system.

Figure 3 shows a generalized structure of the planned material flow management system, including the servers and services required to integrate the system into a single enterprise information environment.

The main task on the way to increase production efficiency for “Silarus” SPA, as well as for all enterprises producing metallurgical silicon, is to reduce the emissions of microsilica.

During the production of one ton of metallurgical silicon, 400–450 kg of dispersed carbonaceous microsilica is formed at the enterprises. The composition of the dust may vary depending on the composition

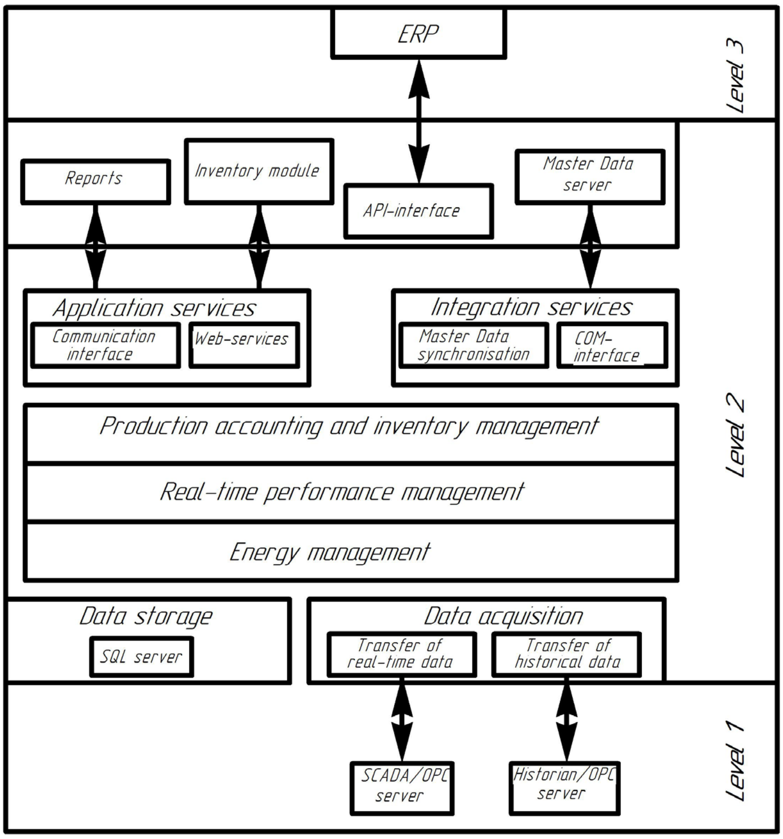

Fig. 3. The generalized structure of the project of the automated material flow management system, planned for further integration into the unified information system of the company "Silarus": level 1 – process control; level 2 – operational production management; level 3 – strategic enterprise management

of the charge and the electric mode of the furnace. The main components are SiO_2 (up to 85 %) and solid carbon (7–8 %), as well as silicon carbide (5 %).

Due to its high activity, this type of raw material, after separation into carbon and microsilica, can be used as a source of powders in 3D printers manufacturing complex building elements and blocks. In addition, carbon-free microsilica is widely used in the global construction industry as an additive to the main raw materials. Thus, the addition of microsilica allows producers to obtain concretes with special properties: increased durability (resistance to weak acids and seawater), increased compressive strength. The production of silicon carbide powder materials is rapidly developing and has a high cost of the final product: micronized carbide (particle size < 1 microns) for ceramics and nanocarbide (particle size < 1 nm) for high-quality structural ceramics and electroplating.

A variety of options for implementing microsilica puts the task of increasing the capture of dust emissions during silicon smelting in OTF in the first place in terms of production efficiency and resource saving.

The main mechanism for the formation of microsilica dust is active oxidation of liquid silicon melt, while a small fraction (< 1 %) of dust particles is formed when it is sprayed. In the absence of gas treatment system (hereinafter referred to as GTS), 30–40 % of microsilica is released through lantern emissions, the other part is deposited in production areas and collected manually in containers (such as FIBC).

In the presence of special-purpose GTS at the enterprise, and in the case of a comprehensive investment project, “Silarus” SPA plans to ensure 99 % capture of microsilica, and its storage in containers for sale and processing in various directions and commercial products.

However, even in the presence of GTS, silicon dust is extremely thin (about 80 % of the generated dust has a fraction of less than 1 mm) and is poorly captured; its size affects the efficiency of dust collection. The task must be solved comprehensively. Improving the quality of charge materials and strict compliance with the OTF process regime, the introduction of a material flow management system, and operational control of the amount of dust captured can significantly reduce the level of dust emissions in the production of technical silicon [18].

Microsilica dust emission control method

To estimate the amount of dust emissions in the production of metallurgical silicon, there are a number of devices and methods that can be divided into 2 groups according to the measurement method:

1. The measurement takes place directly in the dust and gas flow leaving the furnace. In this method of measurement, optical sensors requiring calibration for a specific production are usually used.
2. Extractive measurements related to sampling. A number of extractive methods for the quantification of solid particles have been tested in the silicon industry, such as

• Gravimetric filters offer a reliable, cheap and simple, but unsuitable for continuous monitoring method for estimating the mass concentration of microsilica emissions;

• Standard Optical Particle Counter (OPC) and Condensation Particle Counter (CPC) are not suitable for silicon enterprises because they detect too low concentrations of solid particles.

Monitoring of waste gases in the production of silicon and its alloys is associated with a number of industry-specific problems:

• The gas temperature in the immediate vicinity of the OTF is very high (about 600 °C), which leads to the need for diluting the gas-dust flow before the contact with the sensitive device in the case of extractive measurements;

• High concentration of solid particles in front of the filter causes rapid wear of measuring instruments installed in gas streams with particles, as well as of the measured data [19].

The described difficulties make it relevant to search for new solutions. Based on the basic physical properties of gas-dispersed media, a method was developed for determining the mass concentration of microsilica dust in OTF exhaust gases by temperature control.

The presence of particles in the gas stream changes the velocity and temperature profiles of the gas and, consequently, the heat transfer that is attributed to the gas. The change in heat transfer in gas-dust flows is primarily a consequence of a change in the heat capacity of the mixture, along with a change in the characteristics of the gas phase flow.

The main mechanisms of increasing heat transfer in the presence of solid particles in the gas stream are due to:

1. transfer of thermal energy by bouncing particles;
2. increasing the heat capacity of the medium;
3. changes in the flow structure due to a higher effective Reynolds number of the suspension.

The heat capacity has the strongest influence on the heat transfer. The dispersed system, represented by gases leaving from OTF (90 % CO, 5 % CO_2, etc.), depending on the concentration of microsilica particles, has a different heat capacity.

Since a dispersed system consists of particles and a medium, the total amount of heat transferred to the system is equal to the sum of the heat transferred to the particles and the dispersion medium. The heat capacity of the dispersed system will be equal to:

$$c_{ds} = \frac{c_p \cdot m_p \cdot \Delta T + c_{dm} \cdot m_{dm} \cdot \Delta T}{m_{ds} \cdot \Delta T},$$

where c_p – particle heat capacity, J/kg * K; m_p – particle mass, kg; ΔT – temperature change, K; c_{dm} – heat capacity of the dispersion medium, J/kg * K; m_{dm} – mass of the dispersion medium, kg; m_{ds} – system weight, kg.

By determining the heat loss in the section of the exhaust gas pipeline, it is possible to indirectly determine the mass concentration of microsilica in the exhaust gases.

Conclusion

The analysis of the existing level of automation of the movement of material flows of silicon production in Russia showed the absence of this important link between the automated process control system and ERP. Automation of individual units and the presence of a lower level of process control cannot completely eliminate the problem of divergence of material balances and the irrational use of energy and material resources. The most effective ways to solve these problems are:

1. expanding the functions of existing control systems;
2. end-to-end enterprise automation;
3. using closed-loop technology.

In the global silicon market, the state of automation today is several steps higher than in Russia.

In most foreign silicon production facilities, the production of metallurgical silicon is an intermediate step in the chain of production of polycrystalline silicon. Due to the multi-stage technology for obtaining the finished product, the complexity of the production chain, the requirements for the level of automation are significantly increasing. At the largest enterprises producing polysilicon (Wacker Polysilicon, REC Silicon, Xinte Energy Co.), the methods described above for solving the problems of controlling the movement of materials and energy resources are implemented, which brings the companies to the leading position in this industry.

In order to keep up with the leaders of foreign production, "Silarus" SPA is developing a qualitatively new project for the production of silicon of different grades in accordance with the concept of closed-cycle production. The project, which aims to combine successful experience of foreign companies, as well as new technologies (high-temperature refining), will become a launching pad for the development and implementation of a specialized automated system for operational management of enterprise resources and waste.

REFERENCES

1. **Timofeev A.K.** Optimizatsyia protsesa polucheniia kremniia na osnove metodov matematicheskogo modelirovaniia. [Optimization of the silicon production process based on mathematical modeling methods]. *Sovremennye Problemi Nauki i Obrazovaniia* [*Modern Problems of Science and Education*], 2014, No. 3, P. 20. (rus)

2. **Nemchinova N.V., Mineev G.G., Tiurin A.A., Iakovleva A.A.** Razrabotka tekhnologii rudnotermicheskoi plavki okuskovannoi shikhty iz tekhnogennogo syr'ia dlia proizvodstva kremniia [Development of the technology of ore-thermal melting of the dipped charge from technogenic raw materials for the production of silicon]. *Izvestiia Vysshikh Uchebnykh Zavedenii. Chernaia Metallurgiia* [*Izvestiya. Ferrous Metallurgy*], 2017, Vol. 60, No. 12, Pp. 948–954. (rus)

3. **Kuvykin V.I., Kuvikina E.V., Matveev A.E, Cychev A.G.** Povyshenie effektivnosti proizvodstva pri ispol'zovanii sistemy soglasovaniia material'nogo balansa [Improving production efficiency using the material balance coordination system]. *Sovremennye Naukoemkie Tekhnologii*, 2019, No. 4, Pp. 36–40. (rus) DOI: 10.17513/snt.37488

4. **Soloveenko N.P.** Programma rascheta material'nogo balansa karbotermicheskogo vosstanovleniia kremniia [Program for calculating the material balance of carbothermic reduction of silicon]. *Molodezhnyi Vestnik Irkutskogo Gosudarstvennogo Tekhnicheskogo Universiteta*, 2012, No. 4, P. 51. (rus)

5. **Solov'eva E.A., Kashtanova I.I.** Formirovanie gosudarstvennoi politiki energosberezheniia [Formation of the state energy saving policy]. *Mining University Journal*, 2008, Vol. 179, Pp. 99–103. (rus)

6. **Lutiagin D.V., Iashin V.P., Zabaikin Iu.V., Iakunin M.Iu.** Ocobennosti i tendentsyi tsifrovoi transformatsyi rossiiskoi gornodobyvaiushchei otrasli [Features and trends of digital transformation of the Russian mining industry]. *Economics: Yesterday, Today and Tomorrow*, 2019, Vol. 9, Iss. 7A, Pp. 147–159. (rus)

7. **Korennaia K.A., Loginovski O.V., Maksimov A.A.** Informatsyonnaia sistema krupnogo promyshlennogo predpriiatiia po proizvodstvu ferrosplavov [Information system of a large industrial enterprise for the production of ferroalloys]. *Vestnik Iuzhno-Ural'skogo Gosudarstvennogo Universiteta. Kompiuternye Tekhnologii, Upravlenie, Radioelektronika* [*Bulletin of the South Ural State University. Computer Technologies, Automatic Control, Radio Electronics*], 2012, No. 23, Pp. 50–57. (rus)

8. **Loginovski O.V., Maksimov A.A.** Informatsyonno upravlencheskaia model' i avtomatizirovannaia sistema predpriiatiia (na primere OAO "Kuznetskie ferrosplavy") [Information and control model and automated system of the enterprise (on the example of JSC "Kuznetskie ferrosplavy")]. *Informatsionnye Resursy i Tekhnologii*, 2005, No. 6, P. 8. (rus)

9. **Korennaia K.A., Loginovski O.V., Maksimov A.A., Shurygin A.N., Zimin A.V.** O napravleniiakh innovatsii dlia krupnykh promyshlennykh predpriiatii (na primere ferrosplavnykh proizvodstv) [On the trends of innovation for large industrial enterprises (by the example of ferroalloy production)]. *Vestnik Iuzhno-Ural'skogo Gosudarstvennogo Universiteta. Kompiuternye Tekhnologii, Upravlenie, Radioelektronika* [*Bulletin of the South Ural State University. Computer Technologies, Automatic Control, Radio Electronics*], 2014, Vol. 14, No. 4, Pp. 107–115. (rus)

10. **Gorshkov V.Iu.** Vnedrenie MES na Aksuskom zavode ferrosplavov [Implementation of MES at Aksuskii ferroalloy plant]. *Journal Automation in Industry*, Oct. 2011, Pp. 9–14. (rus)

11. *Wacker factbook 2019*. Munich, 2019. 79 p.

12. *Wacker Sustainability Report 2017/2018*. Pp. 5–37.

13. REC silicon plant gets new automation, Available: *https://www.plantengineering.com/articles/rec-silicon-plant-gets-new-automation/* (Accessed: 01.10.2020).

14. Supcon. Available: *http://en.supcon.com* (Accessed: 01.10.2020).

15. *Study II (Study on state of the art and next generation photovoltaics the circa group Europe January 2013)*, Pp. 73–75.

16. **Jäger-Waldau A.** *PV Status Report 2018*, JRC Science Hub, 2018, 92 p.

17. **Plotkin B.K., Khaikin M.M.** Formation and development of theoretical principles for mineral resources logistics. *Mining University Journal*, 2017, Vol. 223, Pp. 139–146. (rus)

18. **Nemchinova N.V., Mineeva T.S., Nikanorov A.V.** Problemy ekologicheskoi bezopasnosti aliuminievigo i kremnievogo proizvodstv [Problems of environmental safety of aluminum and silicon production]. *Sovremennye Problemi Nauki i Obrazovaniia* [*Modern Problems of Science and Education*], 2013, No. 3, Pp. 93–101. (rus)

19. **Ida Kero, Svend Gra Dahl, Gabriella Tranell.** Airborne emissions from Si/FeSi production. *Journal of Metals*, 2017, Vol. 69, No. 2, Pp. 365–380.

Received 12.02.2021.

СПИСОК ЛИТЕРАТУРЫ

1. **Тимофеев А.К.** Оптимизация процесса получения кремния на основе методов математического моделирования // Современные проблемы науки и образования. 2014. № 3. С. 20.

2. **Немчинова Н.В., Минеев Г.Г., Тюрин А.А., Яковлева А.А.** Разработка технологии руднотермической плавки окускованной шихты из техногенного сырья для производства кремния // Известия высших учебных заведений. Черная металлургия. 2017. Т. 60. № 12. С. 948–954.

3. **Кувыкин В.И., Кувыкина Е.В., Матвеев А.Е., Сычев А.Г.** Повышение эффективности производства при использовании системы согласования материального баланса // Современные наукоемкие технологии. 2019. № 4. С. 36–40. DOI: 10.17513/snt.37488

4. **Соловеенко Н.П.** Программа расчета материального баланса карботермического восстановления кремния // Молодежный вестник ИрГТУ. 2012. № 4. С 51.

5. **Соловьева Е.А., Каштанова И.И.** Формирование государственной политики энергосбережения // Записки Горного института. 2008. Т. 179. С. 99–103.

6. **Лютягин Д.В., Яшин В.П., Забайкин Ю.В., Якунин М.Ю.** Особенности и тенденции цифровой трансформации российской горнодобывающей отрасли // Экономика: Вчера, Сегодня, Завтра. 2019. Т. 9. № 7-1. С. 147–159.

7. **Коренная К.А., Логиновский О.В., Максимов А.А.** Информационная система крупного промышленного предприятия по производству ферросплавов // Вестник Южно-Уральского государственного университета. Компьютерные технологии, управление, радиоэлектроника. 2012. № 23. С. 50–57.

8. **Логиновский О.В., Максимов А.А.** Информационно-управленческая модель и автоматизированная система предприятия (на примере ОАО «Кузнецкие ферросплавы») // Информационные ресурсы и технологии. 2005. № 6. С. 8.

9. **Коренная К.А., Логиновский О.В., Максимов А.А., Шурыгин А.Н., Зимин А.В.** О направлениях инноваций для крупных промышленных предприятий (на примере ферросплавных производств) // Вестник Южно-Уральского государственного университета. Компьютерные технологии, управление, радиоэлектроника. 2014. Т. 14. № 4. С. 107–115.

10. **Горшков В.Ю.** Внедрение MES на Аксуском заводе ферросплавов // Автоматизация в промышленности. Окт. 2011. С. 9–14.

11. Wacker factbook 2019. Munich, 2019. 79 p.

12. Wacker Sustainability Report 2017/2018. Pp. 5–37.

13. REC silicon plant gets new automation // URL: https://www.plantengineering.com/articles/rec-silicon-plant-gets-new-automation/ (Дата обращения: 01.10.2020).

14. Supcon // URL: http://en.supcon.com (Дата обращения: 01.10.2020).

15. Study II (Study on state of the art and next generation photovoltaics the circa group Europe Jan. 2013). Pp. 73–75.

16. **Jäger-Waldau A.** PV Status Report 2018. JRC Science Hub, 2018. 92 p.

17. **Плоткин Б.К., Хайкин М.М.** Формирование и развитие теории минерально-сырьевой логистики // Записки Горного института. 2017. Т. 223. С. 139–146.

18. **Немчинова Н.В., Минеева Т.С., Никаноров А.В.** Проблемы экологической безопасности алюминиевого и кремниевого производств // Современные проблемы науки и образования. 2013. № 3. С. 93–101.

19. **Ida Kero, Svend Gra Dahl, Gabriella Tranell.** Airborne emissions from Si/FeSi production // J. of Metals. 2017. Vol. 69. № 2. Pp. 365–380. DOI: 10.1007/s11837-016-2149-x

Статья поступила в редакцию 12.02.2021.

THE AUTHORS / СВЕДЕНИЯ ОБ АВТОРАХ

Masko Olga N.
Масько Ольга Николаевна
E-mail: olgamasko.17@gmail.com

Gorlenkov Denis V.
Горленков Денис Викторович
E-mail: denis.gorlenkov@gmail.com