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Article

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Technology audit and production reserves

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Reference: Petrov, Stanislav/Bondarenko, Serhii et. al. (2022). Consideration of the possibility of large-scale plasma-chemical production of nanosilicon for lithium-ion batteries. In: Technology audit and production reserves 3 (3/65), S. 6 - 14.
http://journals.uran.ua/tarp/article/download/259066/257816/601657.
doi:10.15587/2706-5448.2022.259066.

UDC 544.558:544.56
DOI: 10.15587/2706-5448.2022.259066
Article type «Original research»

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CONSIDERATION OF THE POSSIBILITY OF LARGE-SCALE PLASMA-CHEMICAL PRODUCTION OF NANOSILICON FOR LITHIUM-ION BATTERIES

The object of research is the process of obtaining silicon nanomaterials for lithium-ion batteries of energy storage devices, and the subject of research is the technology of gas-phase plasma-chemical synthesis for the production of Si-nanoparticles.

In the course of the study, numerical simulation methods were used, which made it possible to determine the parameters of temperature fields, velocities and concentrations. To study the processes of synthesis of nanopowders, a plasma reactor with an electric arc plasma torch of a linear scheme and using an argon-hydrogen mixture as a plasma-forming gas was developed. To analyze the influence of an external magnetic field on the control of the plasma jet parameters, a series of experiments was carried out using an electric arc plasma torch on plasma laboratory facilities with a power of 30 and 150 kW.

The influence of a magnetic field on the process of formation and evaporation of a gas-powder flow in a plasma jet was studied by determining the configuration, geometric dimensions, and structure of the initial section of the jet. In this case, the dispersed material – silicon powder was fed to the plasma torch nozzle section according to the radial scheme. Experimental confirmation of the phenomenon of elongation of the high-temperature initial section of the plasma jet in a longitudinal magnetic field has been obtained. The experimental results indicate that the creation of a peripheral gas curtain significantly changes the characteristics of heat and mass transfer in the reactor. It should be expected that for optimization it is possible to exclude the deposition of nanosilicon particles on the walls of the reactor and provide conditions for continuous operation. The effect of two-phase flow, heat transfer, and mass flow of nanoparticles, including the surface of a plasma reactor with limited jet flow, in the processes of obtaining silicon nanopowders has been studied. This made it possible to correct a number of technological characteristics of the process of constructive design of the actions of plasma synthesis of nanopowders.

The patterns obtained can be used for constructive and technological design in the creation and development of a pilot plant for high-performance production of nanosilicon powders.

Keywords: *plasma-chemical synthesis, plasma reactor, nanosilicon, silicon electrode, lithium-ion battery, numerical simulation.*

Received date: 26.04.2022
Accepted date: 13.06.2022
Published date: 27.06.2022

How to cite
Petrov, S., Bondarenko, S., Koichi, S. (2022). Consideration of the possibility of large-scale plasma-chemical production of nanosilicon for lithium-ion batteries. Technology Audit and Production Reserves, 3 (3 (65)), 6–14. doi: http://doi.org/10.15587/2706-5448.2022.259066

1. Introduction

It is believed that the most innovative period for energy storage technologies is just beginning and will continue for the next decades. A 50 dollars per kilowatt-hour (kWh) lithium-ion battery (LIB) capable of fast charging over 10,000 cycles and over 1 million EV miles with a calendar life of 30 years is expected to be available in the near future. It will be produced from raw materials available all over the world. To displace fossil fuels, a huge scale of production is needed. This transformation will be driven by demand for electric vehicles and storage for intermittent renewables. This will require a global increase in the production of energy storage batteries from 20 GWh per year for electric vehicles to 2000 GWh per year by 2030 and 30,000 GWh per year (more than 1000 times!) for all electric vehicles and global energy by 2050. Although there are currently advertisements about the possibility of achieving these parameters, however, to put them together in one element inherent in batteries (for example, a 1 million mile battery is not good if it costs 200 dollars per kWh) does not seem possible. It will take up to 10 years of global innovation to achieve the required combination [1]. In reviews [2, 3], the authors consider modern materials for active electrodes, the chemical composition of elements for car batteries, productivity, production, and cost. The theoretical performance limits of a battery are always limited by the key components – anode, cathode, electrolyte and separator.

Modern LIB anodes-electrodes based on graphite materials have a capacity of about 372 mAh/g. Theoretically, the replacement of standard carbon anodes with silicon-based materials increases the anode capacity by almost an order of magnitude, up to 3579 mAh/g [1]. Silicon anodes are expected to be the biggest advanced lithium-ion breakthrough in the near future, as graphite is the weak link in the battery, taking up more space than any other component. The advent of ultra-high capacity silicon (Si) anodes, which can completely replace graphite, increases the energy density of lithium ion cells and can significantly reduce the cost of lithium ion batteries, especially in the energy sector [4]. It has already been proven that the use of silicon instead of graphite as a negative electrode in lithium batteries makes it possible to increase the battery capacity by at least three times, which is only a third of the theoretical potential. From a battery of the same size and weight, it will be possible to achieve several times greater capacity, or vice versa – with the same capacity, reduce the size of the battery several times. The main disadvantage of silicon is its significant swelling when saturated with lithium during recharging with a concomitant increase in mechanical stresses in the volume of the electrode layer, which cause a violation of the electrical contact of the active material with current leads and accelerate corrosion. This results in poor electrode cycling stability. In an effort to increase the specific energy and power of LIB, the main efforts of researchers are aimed at creating silicon nanomaterials [5]. Various silicon nanostructures with a high life cycle have been demonstrated in the literature [4–6]. It has been shown that nano-silicon structures overcome the effects of degradation from volume expansion as a result of their ability to relax stresses. Overall, silicon is considered one of the most promising candidates for the next generation of electrode materials in lithium-ion batteries due to its high theoretical power density [1, 7].

2. The object of research and technological audit

The object of research is the process of obtaining silicon nanomaterials for lithium-ion batteries of energy storage devices, and the subject of research is the technology of gas-phase plasma-chemical synthesis for the production of Si-nanoparticles.

To date, the scientific community has made great strides in the development of silicon-containing anodes, which can provide a significant improvement in energy density [6]. Controlling the volumetric expansion of silicon is crucial. This implies the need to use nanoparticles. The most promising proposals in the literature involve the use of nanostructuring in combination with constructs that can accommodate volume changes during lithiation, such as yolk-shell or porous structures [8]. The final electrode material consists of agglomerated 5 nm silicon nanoparticles encapsulated within micro-sized hollow carbon structures. This ensures a high specific electrode capacity of 1570 mAh/g at 0.25 A/g with a capacity retention of 65 % after 250 deep discharge cycles.

It is pointed out in [1] that even when solving the problem of optimal nanomaterials for LIB, their commercialization is still unsatisfactory for two main reasons. The first reason is complex and expensive methods for obtaining nanomaterials, especially complex morphology. The second reason is the non-commercial standards used to test new nanostructures. Any proposed solution must ultimately stand the test of commercialization. To do this, it is necessary to take into account scalability issues at an early stage of technology development. The cost and quality of silicon powders are the main issues that deserve attention in further research. At the same time, it is proposed to devote more efforts to the development of a system for the production of nanoparticles, which can provide both a given size distribution and compatibility with the scale of processing a ton per year [6]. Fig. 1 shows the characteristics of the anode material for various commercially available silicon particles at the present time.

For indicators in Fig. 1, and testing was done in half-cells, with different starting powders under the same conditions.

Nanopowders of elements and their inorganic compounds can be synthesized by various methods in gas-phase, liquid-phase and solid-phase processes, including physical and chemical deposition from the gas phase (the so-called aerosol methods), deposition from solutions, mechanical grinding, etc. Preparation of nanoparticles in thermal plasma of electric discharges (arc, high-frequency (HF), microwave) is one of the leading areas of research and development to create the foundations of new plasma technologies. Similar in all respects for large-scale production of nanocrystalline silicon powders of various shapes are plasma-jet processes [9].

Carbon-coated silicon nanoparticles are considered a promising anode material for the next generation of lithium-ion batteries, while the development of an economical and environmentally friendly method for their high-throughput synthesis is still difficult, hindering practical implementation. Such studies are important for a deep understanding of plasma fusion processes (Fig. 2) [10] and the development of batteries with excellent performance.

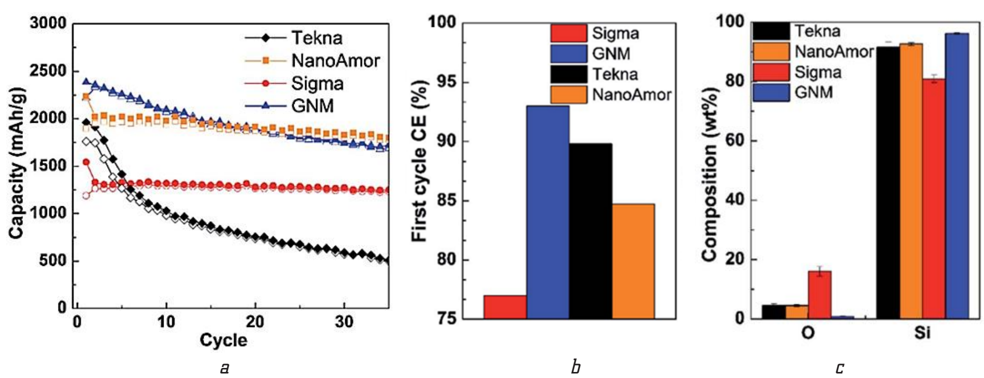


Fig. 1. Characteristics of the anode material for various commercially available silicon particles [6]: *a* – comparison of cycling stability between commercially available silicon nanoparticles; *b* – coulomb efficiency of the first cycle for the four considered powders; *c* – elemental analysis of tested commercially available powders

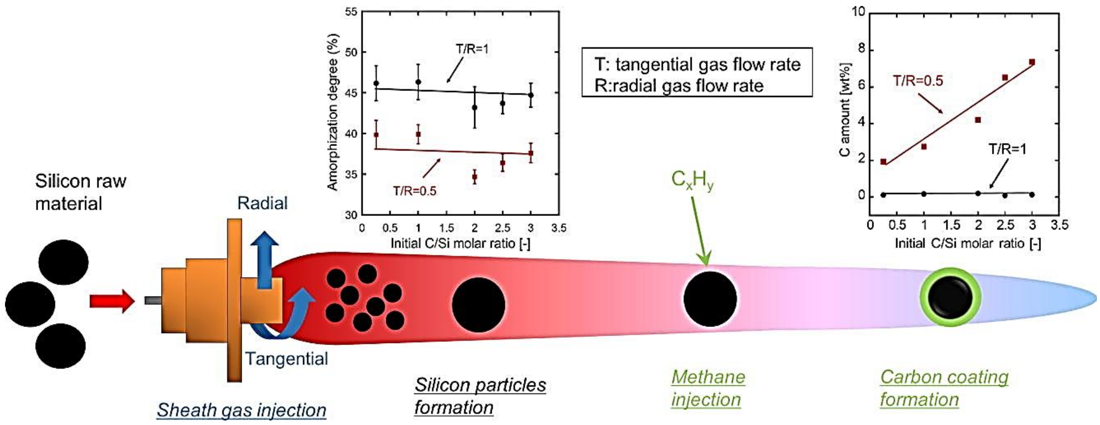


Fig. 2. Synthesis of carbon-coated nanosilicon particles in thermal plasma in one pass [10]

The main conditions for obtaining highly dispersed powders by plasma-chemical synthesis are the reaction proceeding far from equilibrium and the high rate of formation of nuclei of a new phase at a low rate of their growth. Under real conditions of plasma-chemical synthesis, it is advisable to obtain nanoparticles by increasing the cooling rate of the plasma flow in which condensation from the gas phase occurs. This reduces the size of the resulting particles, and also suppresses the growth of particles by merging them upon collision. Plasma-chemical synthesis provides high rates of formation and condensation of the compound and is characterized by a fairly high productivity. Arc plasma torches have the highest power and efficiency.

It is believed that the technology of gas-phase plasma-chemical synthesis has great potential for the production of Si nanoparticles. Compared to other synthesis methods, the gas-phase plasma-chemical process has unique advantages. This is a one-step production, high throughput synthesis capability using the starting material in any desired form (i. e. solid, liquid or gas phase). In addition, the use of tunable plasma parameters provides control over material modification, product morphology, and surface chemistry. Thus, these methods, once developed, can be seen as a step forward for advancing large-scale production.

The purpose of the study stems from the fact that there are challenges in the way of establishing large-scale production of nanosilicon for lithium-ion batteries that must be addressed.

3. The aim and objectives of research

The aim of research is to overcome the problem of high-performance production of cheap silicon nanostructures for LIB, including the scalability of the process.

To achieve this aim, it is necessary to perform the following objectives:

1. Increase the efficiency of evaporation/dissociation of the precursor material of silicon nanoparticles in the region of the high-temperature initial section of the plasma jet.
2. Provide conditions for the continuous removal of the synthesized nanoparticles from the working zone of the reactor.

4. Research of existing solutions to the problem

The problem of the LIB development as a whole is defined [3, 4]. As for the technological features of the plasma, in [11, 12], using the computational method, 3D modeling was performed depending on the time of the plasma jet. It is shown that when a uniform magnetic field is applied due to the Lorentz and Joule heating forces, the flow is laminarized, the plasma jet is elongated, and the temperature profile becomes more filled. This leads to more efficient heating of powder particles and suppression of turbulent diffusion of silicon vapor and nanoparticles by vortices, which in turn affects their formation. Within the framework of the first task, an experimental verification of the efficiency of the theoretically described phenomenon using a hydrogen plasma torch with a power of 30 kW [13] and 150 kW [14] is to be carried out.

To date, plasma reactors with limited jet flow are used in laboratory and pilot units based on arc and HF plasmatrons to obtain various nanopowders. Thus, Tekna Plasma Systems (Canada), a world leader in the field of processes for obtaining and processing powder materials in HF thermal plasma flows, produces units with a power of up to 200 kW, which include a plasma reactor with a limited jet flow [9, 15]. It should be taken into account that in the plasma process of obtaining nanopowders during the flow of a gas-dispersed flow in the reactor, without taking special measures, nanoparticles will be deposited on the wall. The formation of a layer of sintered material will eventually lead to overlapping of the reactor cross section and a complete disruption of the technological regime of the process [16, 17]. To obtain the final product of plasma synthesis in the form of a nanopowder, in which nanoparticles retain the properties determined by the conditions of their formation in a gas flow, it is necessary to exclude or minimize the possibility of physical and chemical transformations in the layer of deposited particles [18, 19]. This can be provided if the temperature in the layer is below a certain threshold value, above which chemical and phase transformations of the nanoparticle material can occur in the layer, as well as their growth. To fulfill this condition, it is necessary to prevent the thickness of the layer of nanoparticles from exceeding the established value by periodically removing the growing layer of particles from the walls of the reactor into hermetic collectors [17]. As part of the second task, the development and experimental verification of the reactor with the continuous removal of the synthesized nanosilicon powder, also under conditions of maximum productivity close to market requirements, is to be developed and experimentally tested.

5. Methods of research

To implement the tasks set, a plasma reactor was developed using an electric arc plasma torch of a linear scheme using an argon-hydrogen mixture as a plasma-forming gas.

With the help of the electromagnet control system, it is possible to change the magnetic induction according to a given law. The influence of a magnetic field on the process of formation and evaporation of a gas-powder flow in a plasma jet was studied by determining the configuration, geometric dimensions, and structure of the initial section of the jet. Dispersed material – silicon powder was fed to the plasma torch nozzle section in a radial pattern.

To analyze the influence of an external magnetic field on the control of the plasma jet parameters, a series of experiments was carried out using an electric arc plasma torch on laboratory plasma units with a power of 30 and 150 kW.

Numerical simulation was used as a tool in the design of the process and reactor for the synthesis of nanopowders, which provided information on the fields of temperatures, rates and concentrations.

6. Research results

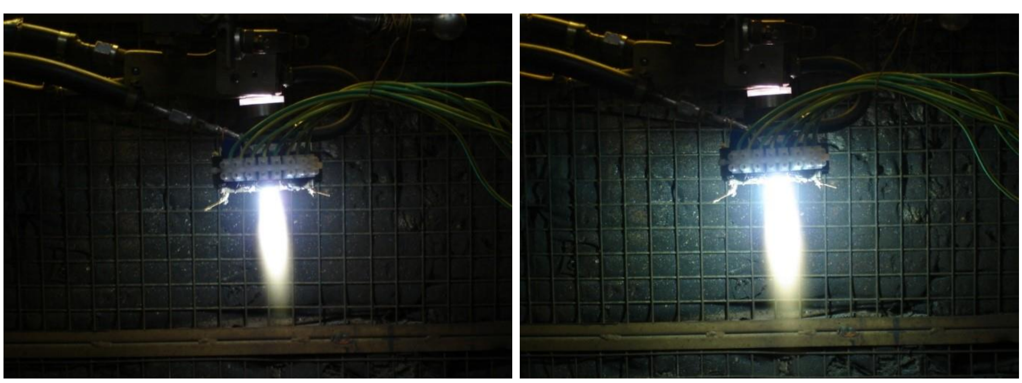
Fig. 3 shows a general view of laboratory plasma units for 30 and 150 kW.

To reveal the influence of an external magnetic field on the control of the plasma jet parameters, a series of experiments was carried out using a linear electric arc plasma torch [13]. The plasma torch is focused on the use of an argon-hydrogen mixture as a plasma gas. The electromagnet is fixed relative to the nozzle system of the plasma torch in such a way that part of the arc column, its section with the attachment spot to the electrode, the initial section of the plasma jet and the nozzle part of the arc channel are located in the zone of action of the magnetic field. The value of the magnetic induction is set by the current in the coil and can be changed according to a given law using the electromagnet control system. The result of the purposeful orientation of the part of the column and the end section of the arc is the rearrangement of the temperature and velocity profile of the plasma jet, which is formed in the nozzle part of the arc channel. This is clearly illustrated in Fig. 4, which shows a view of the plasma jet in the same operating mode of the plasma torch, without an external magnetic field and with an external magnetic field.

The control of the plasma jet parameters is especially important at the stage of evaporation/dissociation of the precursor (in the form of a powder or gas) during the synthesis of nanoparticles [12]. It is known that, in the general case, the transfer channels of the gaseous and solid phases in two-phase flows of such processes do not coincide. This leads to the entry of part of the material being processed into the region of relatively low temperatures and speeds of the working medium. In turn, a consequence of the unequal conditions of heating and acceleration of particles is a decrease in the utilization factor of the source material. Correction of the mutual position of the phases of a two-phase flow will improve this process efficiency indicator to a certain extent. The influence of a magnetic field on the process of formation and evaporation of a gas-powder flow in a plasma jet was studied by determining the configuration, geometric dimensions, and structure of the initial section of the jet. The dispersed material (silicon powder with a particle size, Fig. 5) was fed to the plasma torch nozzle section in a radial pattern.

a *b*

Fig. 3. General view of laboratory plasma units for the synthesis of nanosilicon for: *a* – 30 kW; *b* – 150 kW



a *b*

Fig. 4. View of the plasma jet: *a* – without an external magnetic field; *b* – with an external magnetic field

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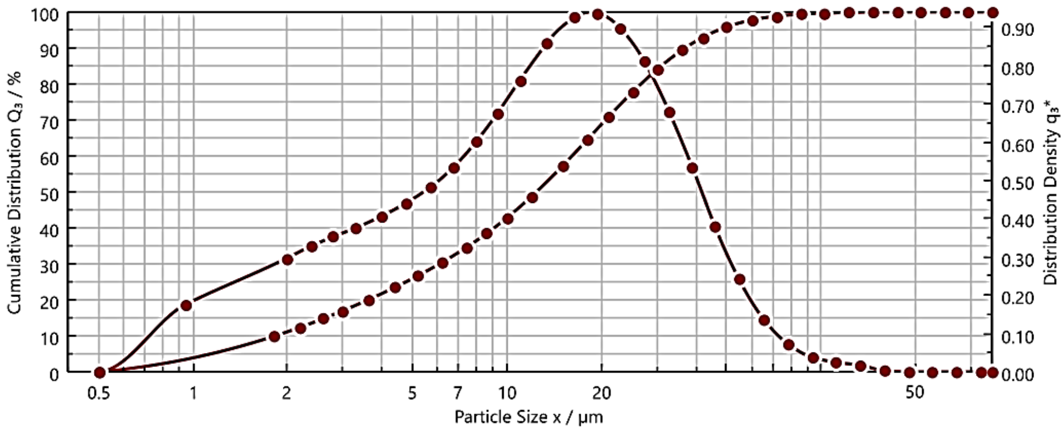


Fig. 5. Particle size of the initial silicon powder

The electrical power of the plasma torch is 30 kW, the useful power is 22 kW. Consumption of plasma-forming gas components: G_{Ar}=3.3 m^3/hour; G_{H2}=0.7 m^3/h. According to the calculated estimates, the specific productivity for the evaporation of silicon powder with a particle size of 5–20 μm in an argon-hydrogen electric arc plasma jet will be up to 10 kW per 1 kg. In the experiments, silicon powder was adopted (Fig. 5) with a consumption of G_{Si}=2.0 kg/h. The flow rate of the transporting argon gas was optimized for a productivity of 2 kg/h in order to blow the powder onto the axis of the plasma jet and was kept constant. The ultimate goal of the experiments was to ensure stable evaporation of the entire powder without the presence of tracks of luminous molten particles at the outlet of the initial section of the plasma jet (Fig. 6).

The work was also aimed at studying two-phase flow, heat transfer and mass flow of nanoparticles, including on the wall of a plasma reactor with a limited jet flow in the processes of obtaining silicon nanopowders. These patterns are important for optimizing technological parameters and designing the processes of plasma synthesis of nanopowders.

The reactor (Fig. 7) is a stationary flow device at atmospheric pressure. It includes a discharge zone of an indirect plasma torch, a unit for introducing raw materials into a high-temperature stream, a reaction volume, a quenching device, a built-in heat exchanger, and a filter for separating condensed products from a gas-dispersed stream.

To date, many computational and experimental studies have been performed on the influence of various factors and parameters in the working zone of a reactor on the processes of formation, growth, and size distribution of silicon nanoparticles under thermal plasma conditions [18–20].

a *b* *c*

Fig. 6. View of the plasma jet: *a* – in the absence of powder supply without a magnetic field; *b* – powder supply without magnetic field; *c* – powder supply with a magnetic field

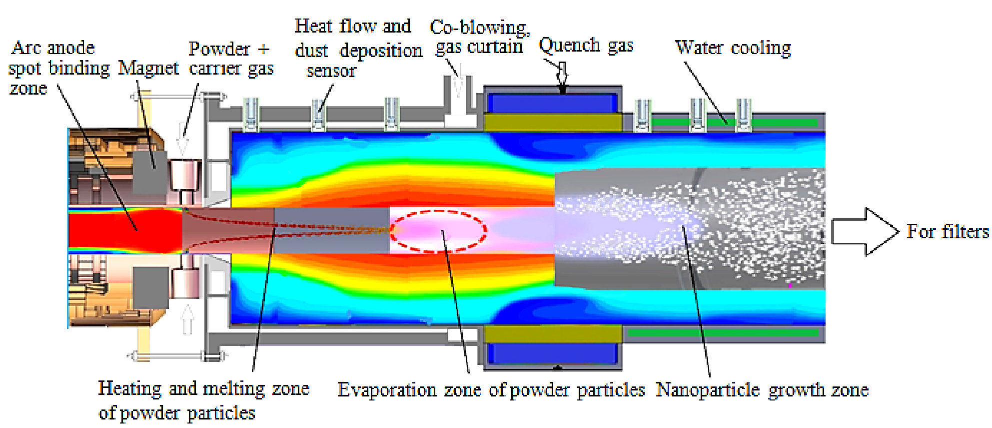


Fig. 7. Electric arc reactor for plasma-chemical synthesis of nanopowders

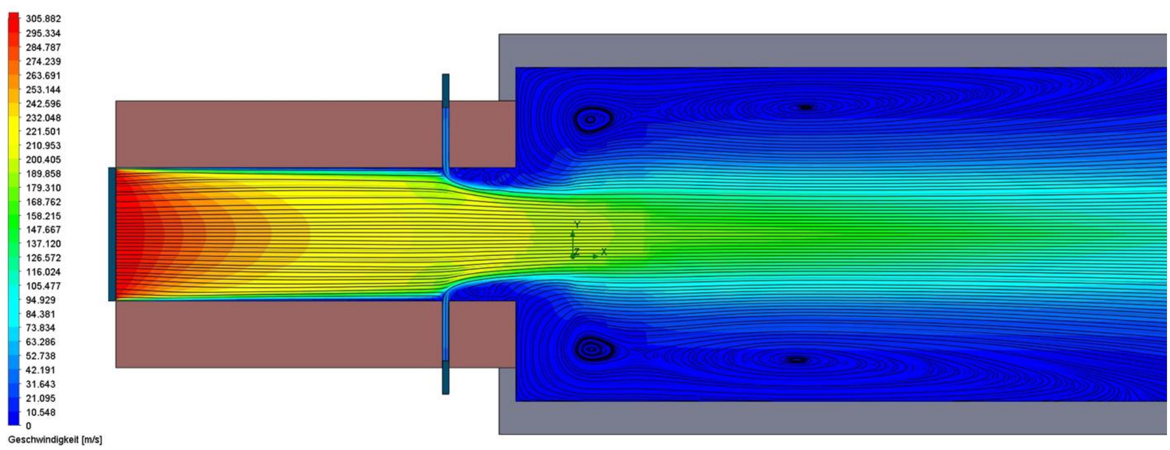
Current methods for producing silicon metal nanopowders are expensive at 30,000 USD/kg, while making silicon metal nanowires is so prohibitive that only government-funded special projects can afford them. Silicon nanopowder is currently produced in small quantities using microwave or induction plasma. For example, commercially available:

1) induction radio frequency plasma unit of the Japanese company JEOL Ltd. TP-40020NPS Thermal Plasma Nanopowder Synthesis System with a power of 6 kW ensures the production of nanopowders with a productivity of 60 g/h [21];

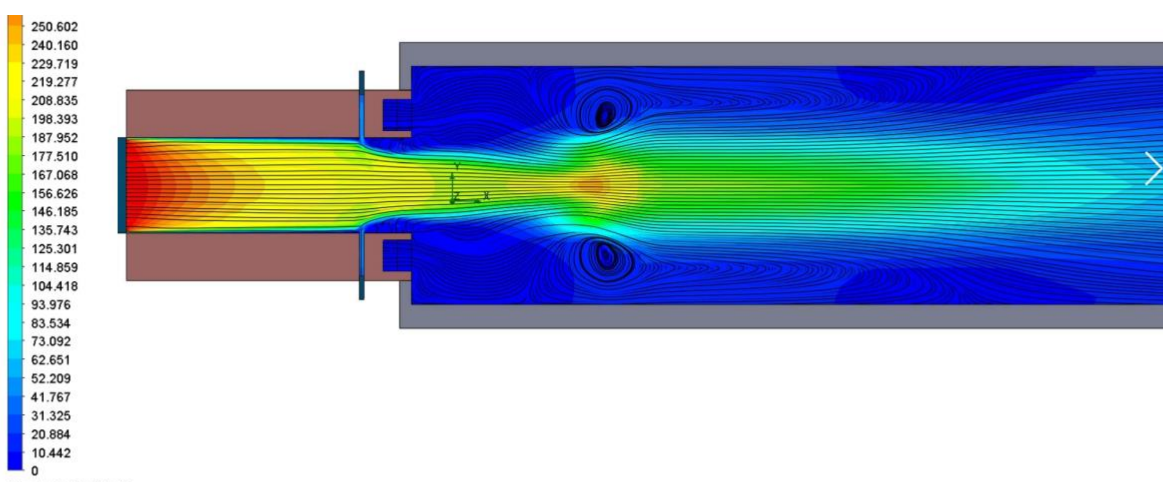
2) the most powerful unit with a capacity of up to 200 kW Teknano-200 Plasma Nanopowder Synthesis of the Canadian company Tekna based on induction plasma technology with working gases (Ar, O_2, N_2, H_2, He, etc.) provides productivity up to several kg/hour of nanomaterials depending on their properties [15].

Based on this, this work is an attempt to demonstrate the possibility of high-performance production of nanosilicon for LIB from cheap and available raw materials – silicon powder of metallurgical quality with a granulometric composition (Fig. 5). The electric arc reactor (Fig. 7) is made according to the traditional scheme. The problem of dispersed phase motion, its heating, melting, evaporation and subsequent condensation into nanoparticles in a plasma jet has been sufficiently studied and has a long history. In essence, in practice, the implementation of this condition is reduced to ensuring sufficient residence time of the polydisperse powder flow in the high-temperature jet until it is completely evaporated. A limited jet flow is realized in the reactor with a sudden expansion of the channel. The channel zone, located behind the sudden expansion – the flow separation section and up to the flow reattachment section, is a recirculation flow zone formed by vortices. Vortices are also formed in the plasma torch channel downstream from the inlet of the powder transported by the gas into the plasma jet. These vortices and subsequent turbulent downstream dispersion are the most critical source of heat and mass transfer of dusty plasma with the reactor walls. This ultimately leads to the deposition of particles on the walls of the reactor and the forced shutdown of the process. Elimination of these phenomena will ensure stable continuous operation of the reactor.

Numerical simulation was used as a tool in the design of the process and reactor for the synthesis of nanopowders, which provided information on the fields of temperatures, rates and concentrations. Fig. 8 shows typical results of plasma reactor simulation in the zone of powder injection into the flame jet and behind the sudden expansion of the exit channel of the anode nozzle of the plasma torch and the entrance of the reactor.



a



b

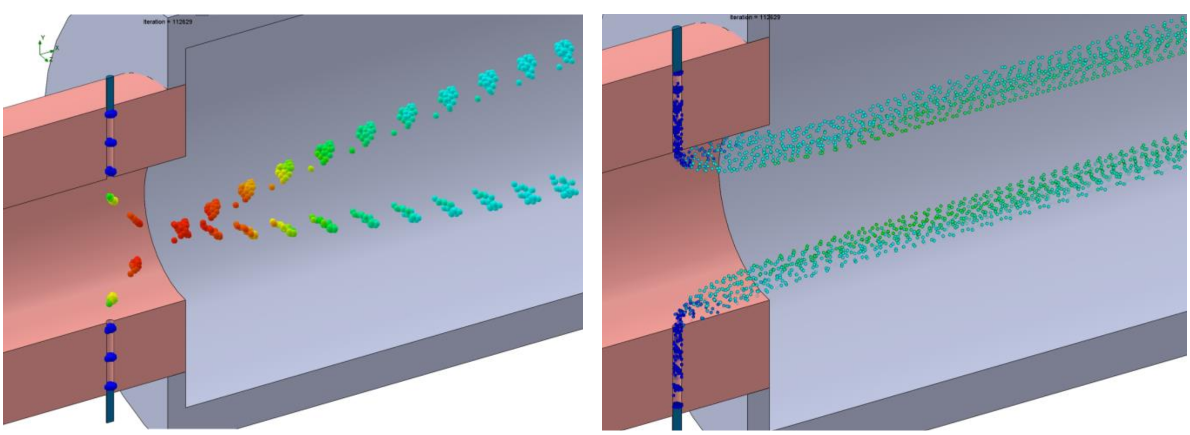
Fig. 8. Vortex flows in the plasma torch anode nozzle channel behind the powder injection site and sudden expansion at the reactor inlet: *a* – without a curtain; *b* – gas curtain through porous injection

The protection of the wall in the recirculation flow zone behind the sudden expansion of the reactor channel and behind the quenching device from the impact of a high-enthalpy two-phase flow with the help of wall gas curtains is adopted. The peripheral flow is swirled or blown through the porous wall. The theory of single-phase curtains under both relatively simple and complex dynamic conditions developing on adiabatic or nonadiabatic surfaces is well developed by now and its foundations are outlined in [22, 23]. Downstream, the effectiveness of the curtain decreases, but it must protect the surface of the reactor wall before the quenching device. The reactor (Fig. 7) uses an annular nozzle with 8 jets, which provides a cooling rate of about $1\cdot10^7$ K/s [24]. The limiting factor is the mixing of the coolant (vapor-gas mixture) with the quenching gas. Mixing is most effective in jets that intensively collide with each other. In this case, the collision of the jets leads to their self-crushing and strong flow turbulence. When organizing mixing according to the principle of uniform distribution of jets, the geometry of the mixing volume and the hydrodynamic parameter ($q=\rho_q w_q^2/\rho_c w_c^2$, where ρ_q, ρ_c, w_q, w_c are the densities and velocities of the quenching gas and coolant, respectively) must satisfy a number of conditions. As a result, the quenching jets, being exposed to the blowing flow, are located in the reactor volume in such a way that their boundary layers completely and uniformly fill the cross section of the mixer (Fig. 9). The range of the jet strongly depends on the value of the hydrodynamic parameter. Here, high precision in the design of mixers based on the principle of uniform distribution of jets is required. To ensure the required range, it is necessary to maintain the value of the hydrodynamic parameter with high accuracy, to minimize flow instability in the mixer due to fluctuations in the flow and energy characteristics of the reactor. Small changes in flow rates and temperature lead to very large range fluctuations. For normal operation of the mixer, it is important that all eight jets of quench gas that are blown into the plasma jet have the same parameters.

According to preliminary estimates, the specific productivity for the target product is about 10 kWh/kg, at which complete evaporation of the silicon powder in the argon-hydrogen plasma jet is achieved. When using a plasma torch with an electric power of 150 kW (Fig. 3, *b*) and a useful power of 100 kW, silicon powder was fed into the reactor (Fig. 7) through two injectors at a flow rate of 5 kg/h. The diameter of the outlet nozzle of the anode of the plasma torch is 20 mm. Plasma-forming gas – argon (75 %) + hydrogen (25 %) with a flow rate of 25 m^3/hour. The temperature at the jet axis is 15000 K. The protective gas is argon (75 %) + hydrogen (25 %) with a flow rate of 10 m^3/hour. Quenching gas – argon (75 %) + + hydrogen (25 %) with a flow rate of 100 m^3/hour. The inner diameter of the reactor is 200 mm, the length to the hardening device is 500 mm. The reactor wall is water-cooled with partial recuperative heat removal to the shielding gas.

The formation of nanoparticles in plasma reactors with a limited jet flow occurs as a result of condensation from the gas phase and is usually accompanied by the deposition of the obtained nanoparticles on the surfaces of the reactor, limiting the high-temperature gas-dispersed flow. The issues of local heat and mass transfer in a plasma reactor are of utmost importance for the implementation of directed plasma synthesis of nanopowders with desired properties. In this regard, an experimental study of the distribution of heat flux densities (Fig. 10) and the mass flow of nanoparticles (Fig. 11) onto the surface of the plasma reactor (Fig. 7) was carried out. To measure the value of the heat flux to the reactor wall, the values of the cooling water flow rate and changes in its temperature were recorded in the heat flux sensors installed on the reactor wall. To estimate the distribution of mass flow density on the reactor wall at the end of the experiment, the powder was collected separately from each sensor and weighed.

The first phase of the process is the evaporation of raw materials at high temperature high-enthalpy thermal arc plasma. The initial silicon particles move along the flow to the tail of the plasma jet, heat up and evaporate. The temperature of the plasma stream rapidly decreases, transferring energy to the feedstock. In the second phase, saturated steam undergoes homogeneous nucleation and heterogeneous condensation during quenching, as a series of processes for obtaining nanoparticles. Arc thermal plasma is a suitable tool for processing silicon with its unique properties such as high thermal conductivity compared to metallic materials, high latent heat of vaporization, and high vaporization temperature. In addition, the synthesis of silicon nanomaterials is affected by the unique characteristics of an electric arc plasma jet: sufficient heat transfer from thermal plasma to silicon in the initial section and a rapid temperature drop beyond it, which is favorable for the second phase of the process.



a *b*

Fig. 9. Range of trajectories of quenching gas jets in the outward plasma flow: *a* – colliding jets; *b* – jets do not penetrate into the core of the flow

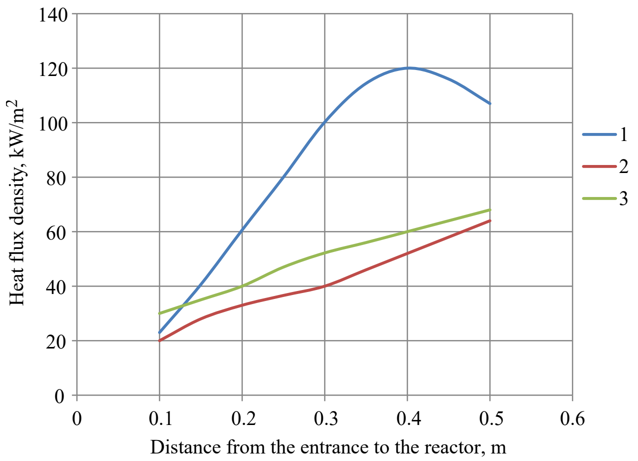


Fig. 10. Distribution of heat flux density on the reactor wall for different operating conditions: 1 – without gas curtain; 2 – with gas curtain; 3 – with gas curtain and powder supply

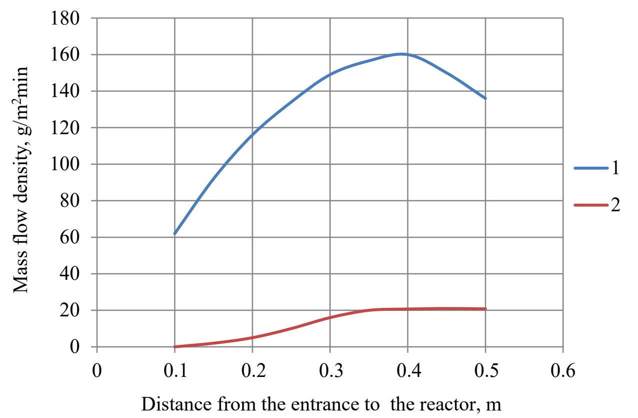


Fig. 11. Distribution of mass flow density on the reactor wall during the synthesis of silicon nanopowders: 1 – absence of a gas curtain; 2 – with gas curtain

Many studies have been carried out on the behavior of an electric arc in a magnetic field: the effect on orientation, movement, energy characteristics in the main column of an arc discharge. At the same time, the possibility of purposeful influence in a magnetic field on the end section of the arc in an indirect plasma torch was confirmed, which leads to a rearrangement of the temperature and velocity profile of the plasma jet, which is formed in the nozzle part of the arc channel [11, 25, 26]. Ultimately, the conditions for the transfer of gas and solid phases in two-phase flows change. The phenomenon of elongation of the high-temperature initial section of the plasma jet in a longitudinal magnetic field has received experimental confirmation (Fig. 4). This improves the heating of the polydisperse phase, with a concomitant increase in productivity and the possibility of using larger powder particles. For the complete evaporation of such silicon raw materials, a sufficiently long residence time in the high-temperature zone is required. An external magnetic field suppresses turbulent eddies. And due to the suppression of turbulent diffusion of silicon vapor and nanoparticles by vortices at the plasma periphery, the formation of a larger nanopowder is expected.

The distribution of heat flux density along the length of the reactor is uneven. In the absence of a gas curtain, it has a maximum in the area of attachment of the boundary layer of the jet to the reactor wall. The value of the heat flux density is determined by radiant and convective heat transfer and depends on the plasma power. The distribution of heat flux density with a gas curtain and a dusty flux vary greatly.

The mass flow density distribution on the reactor wall during the synthesis of silicon nanopowders in the absence of a gas curtain also has an extreme character with a maximum in the zone of jet boundary layer attachment to the wall. The relative proportions of mass flows to the reactor wall remained unchanged even with an increase in the duration of synthesis up to 60 minutes at the given feedstock costs. With an increase in the thickness of the layer of deposited nanoparticles, the heat flux to the reactor wall decreases due to an increase in the thermal resistance of the layer. Moreover, with an increase in the duration of the experiment to 60 minutes, the average size of nanoparticles increases, especially in the zone of maximum heat flux.

To stabilize the high-temperature flow zone in the reactor (Fig. 7) and reduce the scattering intensity by reducing turbulent velocity fluctuations (flow laminarization) and, accordingly, increasing the residence time of the reagents in this zone, a gas curtain in the form of a peripheral vortex flow was used. The presence of a vortex flow created by a swirler leads to a significant change in the distribution of heat and mass flows to the reactor wall (Fig. 10, 11) and a decrease in their magnitude. The experimental results indicate that the creation of a peripheral vortex flow significantly changes the characteristics of heat and mass transfer in the reactor. It should be expected that the optimization can eliminate the deposition of nanosilicon powder on the walls of the reactor and provide conditions for continuous operation.

7. SWOT analysis of research results

Strengths. The first important result of the performed research is an experimental proof of the possibility of a significant increase in the productivity of a plasma-chemical reactor using an electric arc plasma. This was achieved due to two circumstances. The first is the possibility of maximum use of the energy of the plasma jet due to its laminarization in a magnetic field and multi-jet input of raw materials. The second is the provision of a non-equilibrium process, when the rate of evaporation of raw silicon particles in the plasma jet exceeds vapor diffusion with temperature equalization. This ensures the productivity of the process above the equilibrium.

The second important result of the study is the positive use of a gas curtain to ensure a continuous process of synthesis of silicon nanoparticles.

Weaknesses. The patterns obtained are of a general nature, therefore, in the design and technological design, creation and development of a pilot plant, their optimization is necessary.

Opportunities. Further development of the process on the basis of this study should be carried out on the synthesis of nanosilicon particles with a carbon coating in thermal plasma in a single pass (Fig. 2).

External, perhaps, determining factors are solutions to the problem of optimal nanomaterials for LIB, especially complex morphology. It is expected that in the near future, the developers of new batteries will name the most suitable materials. The possibility of obtaining them by

ISSN 2664-9969

a simple and cheap method of plasma-chemical synthesis in an electric arc reactor, which is the subject of this study, will pave the way for the commercialization of the technology.

Threats. The cost of a complete technological cycle for the production of nanosilicon materials suitable for LIB cannot be determined within the framework of this study. However, according to preliminary estimates, the cost of developing and manufacturing a pilot plasma unit with an installed equipment capacity of 320 kVA and a productivity of 17 kg/h will be about 700,000.00 EUR.

8. Conclusions

1. Modeling and experimental verification are carried out on plasma units with a power of 30 and 150 kW. As a result, it is found that the use of additional influences on the plasma jet by a magnetic field at the outlet of the anode nozzle of the plasma torch and a gas curtain at the reactor inlet ensure complete evaporation of the raw silicon powder with specific energy consumption of 10 kWh/kg.

2. The performed studies have shown that the vortex flow of the gas curtain leads to a significant change in the distribution of heat and mass flows to the reactor wall and a decrease in their value in this design by 2 and 7 times, respectively. It should be expected that the optimization can eliminate the deposition of nanosilicon powder on the walls of the reactor and provide conditions for continuous operation.

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