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Mathematical Modeling of Heat Power Processes of Silicium Carbide Production in Acheson Furnace

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Thermo-physical model of silicon carbide production process in Acheson furnace is worked out. Dynamics of thermal state of reaction zone in the furnace is computed by finite difference method with the use of PC. The dimensions of zones of products of silica carbon thermal recovery due to heat generated when passing electric current through the furnace core are determined according to modeling results. Temperature front of reducing reactions is indicated.

Keywords: SILICIUM CARBIDE, ACHESON FURNACE, THERMO-PHYSICAL MODEL, TEMPERATURE ZONES, FRONT OF REDUCING REACTIONS, SECONDARY MATERIALS

Introduction

Silicium carbide is one of major artificial inorganic materials widely applied for manufacture of abrasive tools, high-temperature radiators, refractory ceramic as well as in metallurgy. The most part of silicium carbide in the world industry is produced by method suggested by Acheson in the end of 19th century [1].

The method consists in carbon-thermal reduction of silicon due to Joule heat generated when electric current passing through the furnace core. The principal scheme of self-moving resistance furnace is presented in **Figure 1**.

SiC production process is very labor-consuming and requires significant power consumption 7300-7600 kW·h/t. According to [2], amount of electric energy in the structure of cost price of silicium carbide of abrasive quality is 50-60 %, at burden distribution 60-70 t, commercial yield is 10.5-11.5 tons (15-19 %). Therefore, maintenance of maximum product yield at the rational charge of electric energy is an important industrial problem.

The most precise methods of SiC production process control are based on direct measurements of reaction zone temperature. However, high temperature and corrosive environment make it almost impossible to apply direct methods of temperature control with the use of thermocouples or pyrometers. Indirect methods based on measurement of electrical resistance or acoustic emission signals are not used because of errors. Therefore, the process is controlled by empirically determined diagrams of dynamics of lead-in power [2] (**Figure 2**).

In this case, the key criterion of power regime control is charge material capability and type of produced silicium carbide. Information about processes of furnace thermal field formation and parameters of chemical reactions initiated by this field is required for development of rational technological regimes of SiC production by Acheson`s method. Therefore it is reasonable to use mathematical modeling in order to receive information about these processes.

Results and Discussion

Retrospective of investigations and publications

A number of publications, for example [3, 4], are devoted to investigation of heat and power processes in Acheson furnace. These works present methodology of construction of mathematical models of this process. The current level of mathematical modeling and development of personal computer enables to remove the specified restrictions. The task of present research is working out of computer model of thermal condition of Acheson furnace reaction zone which will enable to develop further technological

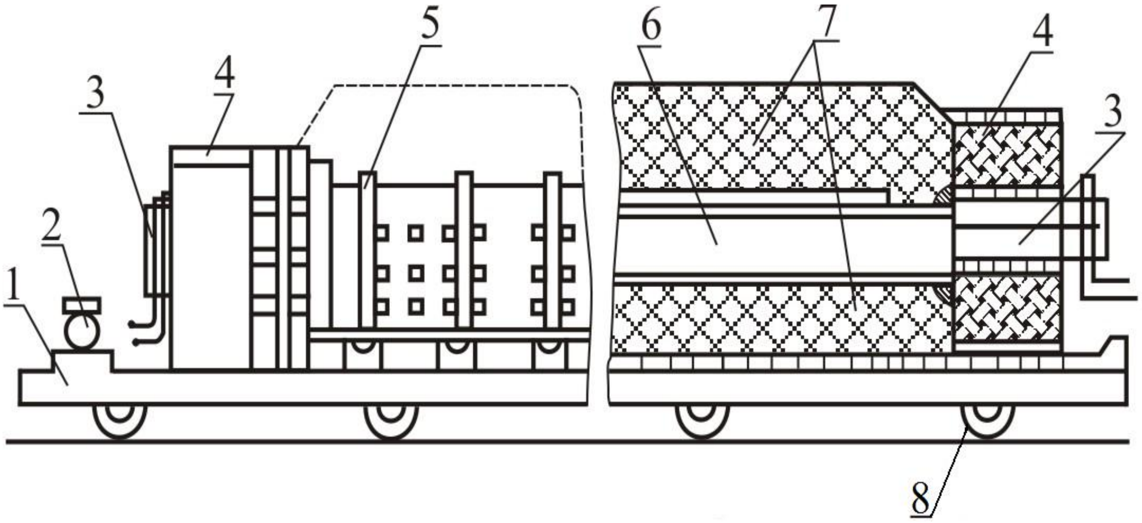

Figure 1. Self-moving electric resistance furnace for production of silicium carbide: *1* - carriage; *2* – furnace travel mechanism; *3* - electrocontact knots; *4* - fire brick face walls; *5* - side shields; *6* - working electrical resistance; *7* - burden; *8* - wheel pair

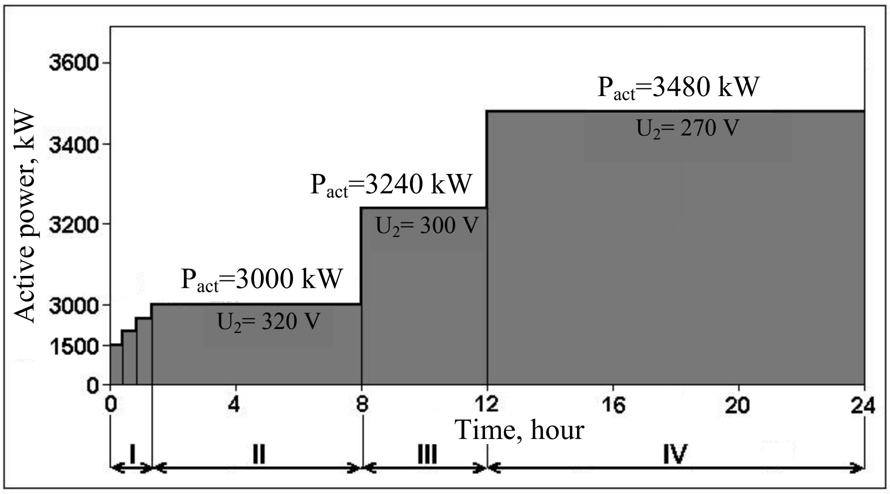

Figure 2. Dynamics of lead-in power during the process of silicium carbide production: I (0-1.5 h) - power 1500-3000 kW; II (1.5-8 h) - power 3000 kW; III (8-12 h) - power 3240 kW; IV (12-24 h) - power 3480 kW

recommendations concerning conduct of silicium carbide production process.

Thermo-physical model of the process

Acheson furnace is a complicated power-technological and thermo-physical unit in view of mathematical modeling.

The main heat source is electric energy during silicium carbide production process. Electric power of furnace is supplied from monophase transformer (**Figure 3**).

The furnace transformer of ЭОЦН 8200-10 type has set power 4000 kV·A, current capacity in high-tension winding taking into account overheating is ≤400A. Voltage from the high side is 10.5-11 kV, low - 408-206 V (17 steps of voltage change).

Heat current formed in the center with cross-section 0.6×0.8 m is distributed from internal zones of the furnace towards external zones. Due to warming-up of reaction burden, the process of carbide formation starts in the center and then is distributed in the contiguous zones. Total reaction of carbon-thermal process of high-silica sand interaction with carbon is as follows:

$$SiO_2+3C = SiC+2CO$$
$$\Delta G=555615-322,11\cdot T,\ \text{kJ/mole} \qquad \text{(Eq. 1)}$$
$$\Delta G = 0,\ \text{if}\ T = 1725\ K$$

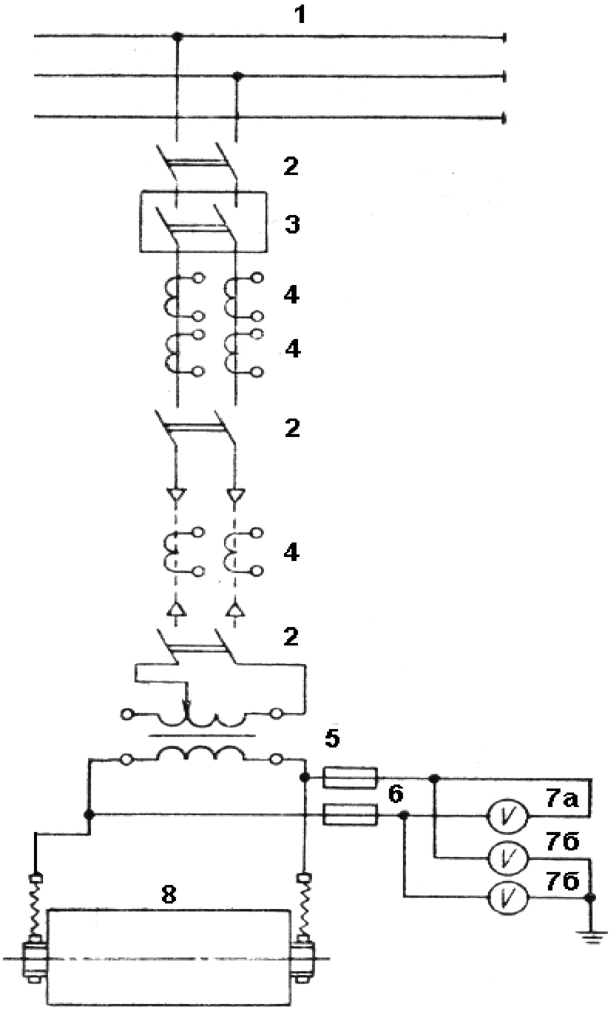

Figure 3. Schematic circuit diagram of turning resistance furnace on for silicium carbide production with power 4000 kV·A: *1* - high voltage tyres (10 kV); *2* - air-break disconnectors (type РВФ-10/600); *3* - oil circuit breaker (type ВМГ-10, 10/600); *4* - instrument current transformer (type ТПЛ-10-0.5/Р-400); *5* - furnace transformer; *6* - thermal links; *7* - voltmeter gauges (type Э-378) for linear (*a*) and phase (*b*) voltage; *8* - resistance furnace

There are four temperature zones in the resistance furnace [3, 5, 6].

1. T < 1452 °C. At these temperatures there is no interaction of components – composition of initial and end products is almost the same.

2. 1452 °C < T < 2609 °C. The main siliceous product is silicium carbide in reaction products at excess of carbon, and at deficiency of carbon - SiO_2 recovery takes place only until the formation of gaseous monosilicon oxide.

3. 2609 °C < T < 2927 °C. In this temperature interval silicium is the basic reduction product.

4. T > 2927 °C. In this area of temperatures all siliceous products of reactions at any relationship of initial components can be only in gaseous state.

The furnace operates in unsteady thermal regime therefore heat losses increase in due course. Temperature conditions of the furnace define the process of silicium carbide formation. Thus, the following factors have effect on dynamics of thermal condition of furnace: energy generated in the center of furnace, energy consumption due to endothermic reactions, significant amount of off gases, heat transfer in the environment. Taking into account lay-out of furnace center along the whole length of the furnace we assume uniform energy generation from a core surface.

When estimating dynamics of thermal condition of furnace lining we consider that heat currents are directed only in axial direction. Therefore in this paper we consider a two-dimensional model of heat transfer in the furnace volume and one-dimensional model of heat transfer in fireclay lining through the bottom and side walls. Then differential equations of heat conduction for furnace laboratory (2) and linings will be as follows (3) [3]:

$$C_s\left(T_s\right)\cdot\rho_s\frac{\partial T_s}{\partial\tau}=\left(\frac{\partial}{\partial x}\left[\lambda_s\left(T_s\right)\frac{\partial T_s}{\partial x}\right]+\frac{\partial}{\partial y}\left[\lambda_s\left(T_s\right)\frac{\partial T_s}{\partial y}\right]-C_{gas}\cdot\rho_{gas}\cdot\upsilon_l\left(\tau\right)\cdot T_{gas}\right)-\frac{\rho^0}{\nu\cdot\mu}\cdot Q_{SiC}\frac{d\eta}{d\tau}$$

(Eq. 2)

$$C_l(T_l)\cdot\rho_l\cdot\frac{\partial T_l}{\partial\tau}=\frac{\partial}{\partial x}\left(\lambda_l(T_l)\frac{\partial T_l}{\partial x}\right)\quad\text{for furnace walls}$$

$$C_l(T_l)\cdot\rho_l\cdot\frac{\partial T_l}{\partial\tau}=\frac{\partial}{\partial y}\left(\lambda_l(T_l)\frac{\partial T_l}{\partial y}\right)\quad\text{for furnace bottom}$$

(Eq. 3)

where $C_s(T_s)$, $C_l(T_l)$, C_{gas} - specific heating capacities of charge materials, lining and waste gas; ρ_C, ρ_l, ρ_{gas} - densities; $\lambda_s(T_s)$, $\lambda_l(T_l)$ - coefficients of thermal conductivity of charge materials and lining; $v_l(\tau)$ - rate of gas filtration; T_{gas} - gas temperature; ρ^0 - initial concentration of charge materials; v, μ - stoichiometric coefficient and molecular weight of initial charge materials; Q_{SiC} - thermal effect of reaction of silicium carbide formation; η - depth of transformation of initial materials. As we know power generated on a core, boundary conditions of the 2nd rate for interface furnace center - furnace laboratory are as follows:

$$-\lambda_s\left(T_s\right)\cdot\left(\frac{\partial T}{\partial x}+\frac{\partial T}{\partial y}\right)=q_s\left(\tau\right)\qquad\text{(Eq. 4)}$$

where $q_s\left(\tau\right)$ - unit power generated on a core (**Figure 2**). Boundary conditions of the 4th rate on the interface of furnace work zone and lining are:

$$\left.\begin{aligned}&T_{c.external}=T_{l.internal}\\&\lambda_s(T_s)\cdot\left(\frac{\partial T_s}{\partial n}\right)_{n_{s.external}}=\lambda_l(T_l)\cdot\left(\frac{\partial T_l}{\partial n}\right)_{n_{l.internal}}\end{aligned}\right\}\qquad\text{(Eq. 5)}$$

where $T_{c.external}$ - temperature of external surface of the charge, $T_{l.internal}$ - temperature of internal surface of lining. As the furnace top is open and gas is removed from the surface as a reaction product, we accept boundary conditions of the 3rd rate on the interface of furnace work zone and environment:

$$-\lambda_s\left(T_s\right)\frac{\partial T}{\partial y}=\left(\alpha_{envl}+c_{gas}\cdot\rho_{gas}\cdot\upsilon_l\left(\tau\right)\right)\cdot\left(T_{c.external}-T_{env}\right)$$

(Eq. 6)

where α_1 - coefficient of heat-to-environment transfer from furnace surface; T_{env} – environment temperature. For interface lining – environment boundary conditions of the 3rd rate will be as follows:

$$-\lambda_l\cdot\left(\frac{\partial T_l}{\partial n}\right)_{n_{l.external}}=\alpha_{env2}\cdot\left(T_{l.external}-T_{env}\right)$$

(Eq. 7)

where α_2 - coefficient of heat-to-environment transfer from furnace bottom and walls.

When solving this task we assume that in the initial moment of time the temperature inside furnace and lining and environment temperature are equal.

Modeling and analysis results

Dynamics of thermal condition of furnace reaction zone was computed by finite difference method with the use of PC. Results of modeling are illustrated in **Figure 4**.

Zone development of reduction processes causes the formation of intermediate products of reduction reactions except for silicium carbide.

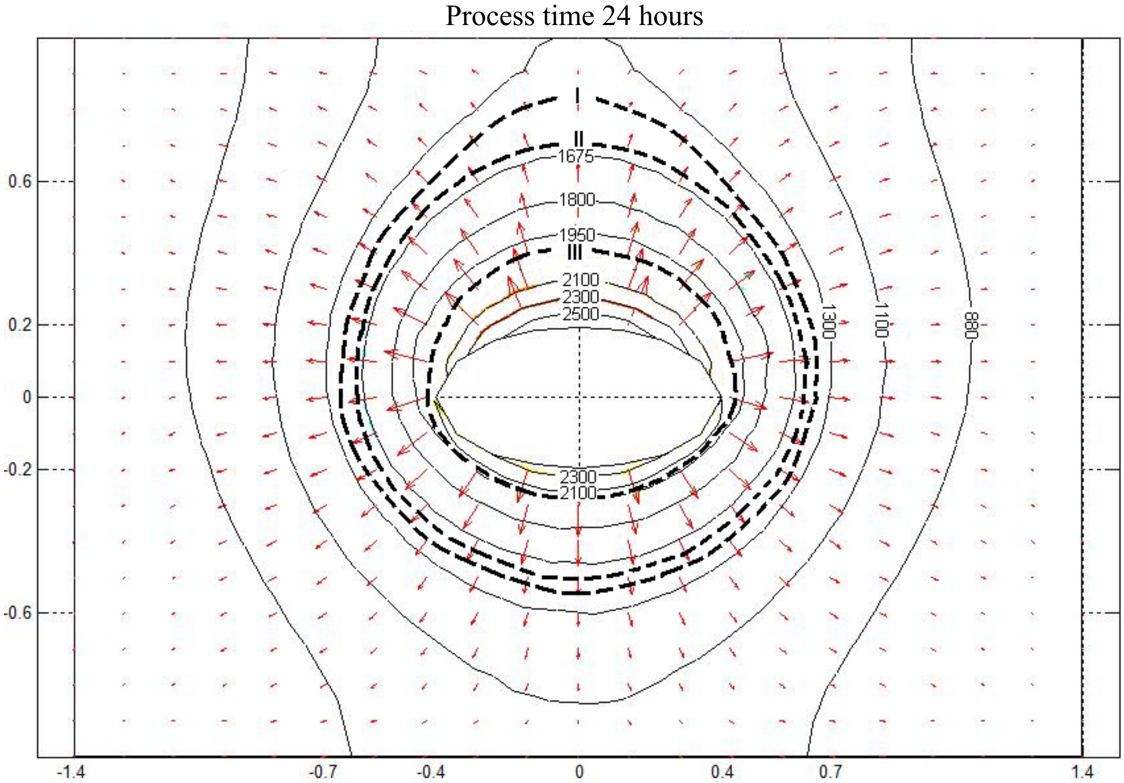

Figure 4. Temperature pattern distribution across the section of reaction zone of Acheson furnace after heating during 24 hours: zone I - formation of intermediates of reaction of silicon reduction by carbon (siloxicon and aggregates - 40-60 % SiC); zone II – amorphous area, crystals β - SiC (70-85 % SiC); zone III – macro-crystalline abrasive α - SiC (92-98 % SiC)

1. Zone I - area of formation of intermediate products of silica reduction by carbon. Presented by siloxicon and aggregates containing 40-60 % SiC.
2. Zone II - amorphous area presented by crystals β - SiC (70-85 % SiC).
3. Zone III – macro-crystalline abrasive α - SiC (92-98 % SiC).

Dimensions of zones of formed products of carbon-thermal silica reduction due to heat are defined according to modeling results, the temperature front of reducing reactions is marked out. It is determined that zone of siloxicon and aggregates (I) is 60 mm thick in the bottom and side parts and 190 mm in the top. Sizes of amorphous zone (II) presented by crystals β - SiC are 250 mm and 340 mm. The area of coarse silicon carbide (III) in the bottom and side part is 120 mm thick and 300 mm thick in the top. Asymmetry of zones is caused by upward currents of hot gases.

Conclusions

1. Thermo-physical model of silicon carbide production process in Acheson furnace is developed.
2. Dynamics of thermal condition of furnace reaction zone is computed by finite difference method with application of PC.
3. Zones of existence of products of carbothermic reduction of silica are sized up by results of modeling.
4. It is reasonable to estimate effect of input power dynamics on sizes of zones of reduction products by means of developed model in order to obtain analytical dependences of change of thermal condition of furnace reaction zone which will enable to work out technological recommendations on conduct of silicium carbide production process and to develop Automatic Process Control System of furnace.

References

1. W. D. Boecker. *Paper Fachberichte*, 1997, No. 5, pp. 244-251.
2. A. N. Porada, M. I. Gasik. *Electrothermics of Anorganic Materials,* Moscow, Metallurgy, 1990, 232 p.*
3. S. D. Amosov, U. I. Gol`dshleger, A. G. Merzhanov. *Theoretical and Experimental Research of Carbothermic Process of Silicon Reduction*, Chernogolovka, Preprint, 1985, 78 p. *

4. B. I. Khaikin. *Burning Processes in Chemical Engineering and Metallurgy,* Chernogolovka, 1975, pp. 227-244. *
5. U. I. Gol`dshleger, A. G. Merzhanov. *Reports of Academy of Sciences of USSR*, 1983, Vol. 269, No. 5, pp. 1107-1111. *
6. I. V. Ryabchikov, A. V. Gorokh, M. S. Khruschev, et al. *Izvestiya Academii Nauk USSR. Metally*, 1966, No. 4, pp. 38-43. *

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Математическое моделирование теплоэнергетических процессов производства карбида кремния в печи Ачесона

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Разработана теплофизическая модель процесса производства карбида кремния в печи Ачесона. Методом конечных разностей с применением ПЭВМ выполнен расчет динамики теплового состояния реакционной зоны печи. По результатам моделирования определены размеры зон образовавшихся продуктов углеродотермического восстановления кремнезема за счет тепла, выделяющегося при пропускании электрического тока через керн печи, обозначен температурный фронт протекания восстановительных реакций.