RESEARCHING OF THERMOPHYSICAL PROCESSES IN ACHESON FURNACE FOR THE PRODUCTION OF SILICON CARBIDE[1]

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ABSTRACT

A thermo-physical model of silicon carbide production process in an Acheson furnace has been successfully developed. The dynamics of the thermal state of the reaction zone in the furnace is computed by finite difference method with the use of a PC. The dimensions of zones of products of silica carbon thermal recovery due to the heat generated when passing electric current through the furnace core are determined according to modeling results. The temperature front of reducing reactions is indicated.

INTRODUCTION

Silicon carbide is one of the major artificial inorganic materials widely applied in the manufacture of abrasive tools, high-temperature radiators, refractory ceramics as well as in metallurgy. The largest amount of silicon carbide in the world industry is produced by the method suggested by Acheson at the end of the 19th century [1]. The method consists of the carbon-thermal reduction of silicon due to the Joule heat generated when electric current is passing through the furnace core. The principal scheme of self-moving resistance furnace is presented in Figure 1.

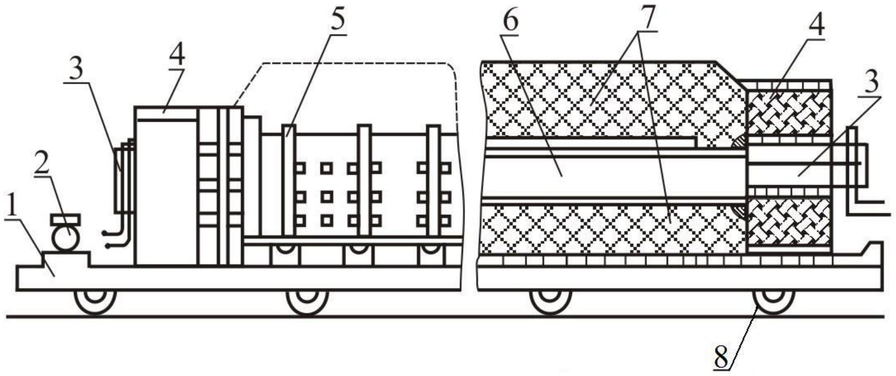

Figure 1: Self-moving electric resistance furnace for production of silicon carbide: 1 - carriage; 2 – furnace movement mechanism; 3 - electrocontact nodes; 4 - fire brick face walls; 5 - side shields; 6 - working electrical resistance (core); 7 - burden; 8 - wheel pair [2]

The SiC production process is very labor-consuming and requires significant power consumption of 7300-7600 kW·h/t. According to [2], the proportion of electric energy in the cost price of silicon carbide of abrasive quality is 50-60 %, from a charge of 60-70 t, the commercial yield is 10.5-11.5 tons (15-19%). Therefore, maintaining 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 the temperature in the reaction zone. However, the 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].

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[1] This work was performed by the leadership of academician NASU, Doctor in Technical Science, prof. Gasik M.I.

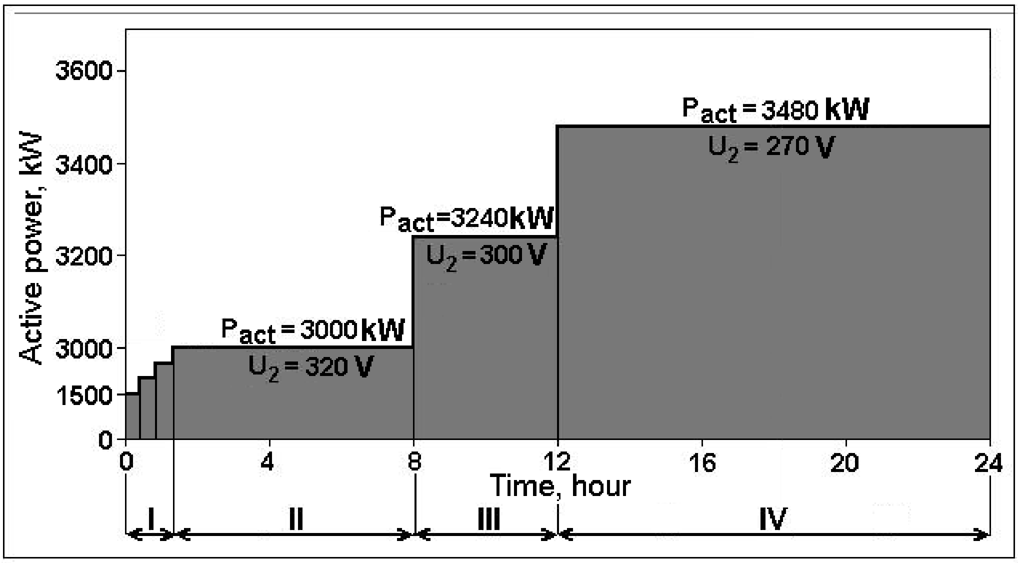

Figure 2: Dynamics of lead-in power during the process of silicon carbide production: I (0-1.5 h) - power 1500-3000 kW; II (1.5-8 h) - power 3000 kW; III (8-12 h) - power 3240 kW; IV (12-24 h) - power 3480 kW [2]

In this case, the key criterion of power regime control is charge material capability and the type of silicon carbide produced. 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.

RETROSPECTIVE OF RESEARCHES AND PUBLICATIONS

A number of publications, for example [3, 4], are devoted to the investigation of heat and power processes in an Acheson furnace. These works present methodologies of the construction of mathematical models of this process. The current level of mathematical modeling and development of the personal computer allow the removal of the specified restrictions. The task of present research is o develop a computer model of the thermal condition of the Acheson furnace reaction zone which will allow development of further technological recommendations concerning the silicon carbide production process.

THERMO-PHYSICAL MODEL OF THE PROCESS

The Acheson furnace is a complicated power-technological and thermo-physical unit from the point of viewof mathematical modeling. The main heat source is electric energy during the silicon carbide production process. The electric power of furnace is supplied from monophase transformer (Figure 3).

Heat current formed in the center is distributed from internal zones of the furnace towards external zones. Due to warming-up of the reaction charge, the process of carbide formation starts in the center and then is distributed in the contiguous zones. The total reaction of carbon-thermal process of high-silica sand interaction with carbon is as follows:

$$SiO_2+3C = SiC+2CO; \quad \Delta G=555615-322{,}11\cdot T, \text{ kJ/mole} \qquad (1)$$

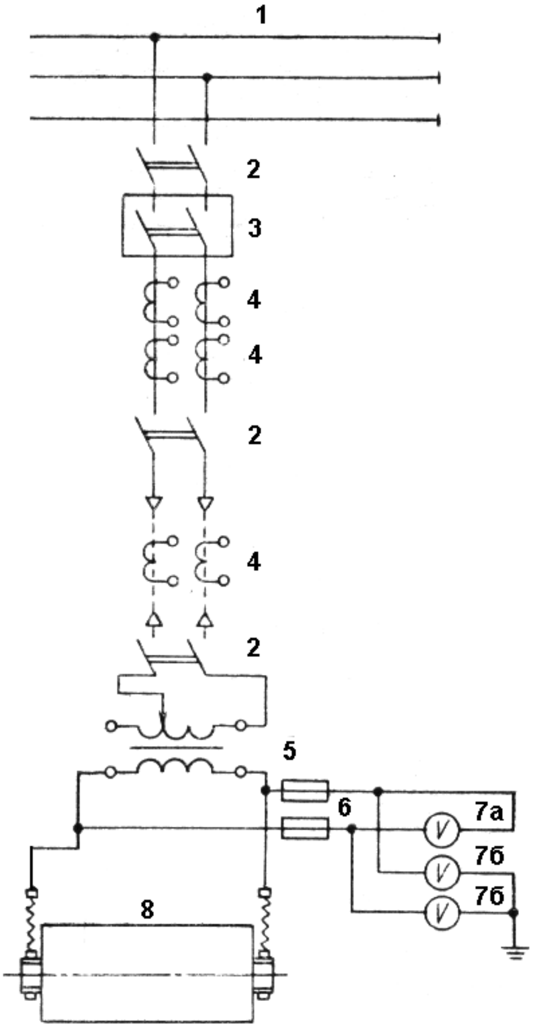

Figure 3: Schematic circuit diagram of turning resistance furnace on for silicon carbide production with power 4000 kV·A: 1 - high voltage bus (10 kV); 2 - air-break disconnectors (type РВФ-10/600); 3 - oil circuit breaker (type ВМГ-10, 10/600); 4 - measuring current transformer (type ТПЛ-10-0.5/Р-400); 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 – the composition of initial and end products is almost the same.

2. $1452\ °C < T < 2609°C$. The main siliceous product is silicon carbide in reaction products at excess of carbon, and with a deficiency of carbon - SiO2 recovery takes place only until the gaseous monosilicon oxide is formed.

3. $2609\ °C < T < 2927°C$. In this temperature interval silicon 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 loss increases in due course. The temperature conditions of the furnace define the process of silicon carbide formation. Thus, the following factors have effect on dynamics of the thermal condition of the furnace: energy generated in the center of the furnace, energy consumption as a result of endothermic reactions, significant amount of off-gases, and heat transfer in the environment. Taking into account the lay-out of the furnace center along the whole length of the furnace we assume that uniform energy is generated from a core surface. When estimating dynamics of thermal condition of furnace lining we consider that heat currents are directed only in the 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 the 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]:

$$C_s(T_s)\cdot\rho_s\frac{\partial T_s}{\partial\tau}=\left(\frac{\partial}{\partial x}\left[\lambda_s(T_s)\frac{\partial T_s}{\partial x}\right]+\frac{\partial}{\partial y}\left[\lambda_s(T_s)\frac{\partial T_s}{\partial y}\right]-C_{gas}\cdot\rho_{gas}\cdot\upsilon_f(\tau)\cdot T_{gas}\right)-$$
$$-\frac{\rho^0}{\nu\cdot\mu}\cdot Q_{SiC}\frac{d\eta}{d\tau}\quad, \qquad (2)$$

$$\begin{aligned}&C_l(T_l)\cdot\rho_l\cdot\frac{\partial T_l}{\partial\tau}=\frac{\partial}{\partial x}\left(\lambda_l(T_l)\frac{\partial T_l}{\partial x}\right)\ \text{for furnace walls}\\&C_l(T_l)\cdot\rho_l\cdot\frac{\partial T_l}{\partial\tau}=\frac{\partial}{\partial y}\left(\lambda_l(T_l)\frac{\partial T_l}{\partial y}\right)\ \text{for furnace bottom}\end{aligned}\quad, \qquad (3)$$

where: Cs(Ts), $C_l(T_l)$, C_{gas} - specific heating capacities of charge materials, lining and waste gas;
ρ_C, ρ_l, ρ_{gas} - densities;
λs(Ts), $\lambda_l(T_l)$ - coefficients of thermal conductivity of charge materials and lining;
$v_f(\tau)$ - rate of gas filtration;
Tgas - gas temperature;
ρ_0 – initial concentration of charge materials;
ν, μ - stoichiometric coefficient and molecular weight of initial charge materials;
Q_{SiC} – thermal effect of reaction of SiC formation;
η - depth of transformation of initial materials.

INITIAL AND BOUNDARY CONDITIONS

There are the following boundary conditions while solving this task [7]:

- the 2nd rate for interface furnace center - furnace laboratory (as we know, power generated on a core)

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

where $q_s(\tau)$ - unit power generated on a core (figure 2).

- the 4th rate on the interface of furnace work zone and lining

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

where: $T_{c.external}$ - temperature of external surface of the charge,

$T_{l.internal}$ - temperature of internal surface of lining.

- the 3rd rate on the interface of furnace work zone and environment (as the furnace top is open and gas is removed from the surface as a reaction product)

$$-\lambda_s(T_s)\frac{\partial T}{\partial y}=\left(\alpha_{env_1}+c_{gas}\cdot\rho_{gas}\cdot\upsilon_1(\tau)\right)\cdot\left(T_{c.external}-T_{env}\right) \qquad (6)$$

where: α_{env_1} - coefficient of heat-to-environment transfer from furnace surface,

T_{env} - environment temperature.

- the 3rd rate for interface lining – environment.

$$-\lambda_l\cdot\left(\frac{\partial T_l}{\partial n}\right)_{n_{l.external}}=\alpha_{env_2}\cdot\left(T_{l.external}-T_{env}\right) \qquad (7)$$

where: α_{env_2} - coefficient of heat-to-environment transfer from furnace bottom and walls.

We assume that in the initial moment of time the temperature inside furnace and lining and environment temperature are equal.

MODELING AND ANALYSIS RESULTS

The dynamics of the thermal condition of the furnace reaction zone was computed by finite difference method with the use of a PC. The results of modeling are illustrated in Figure 4 and 5 [7]. Zone development of reduction processes causes the formation of intermediate products of reduction reactions except for silicon carbide.

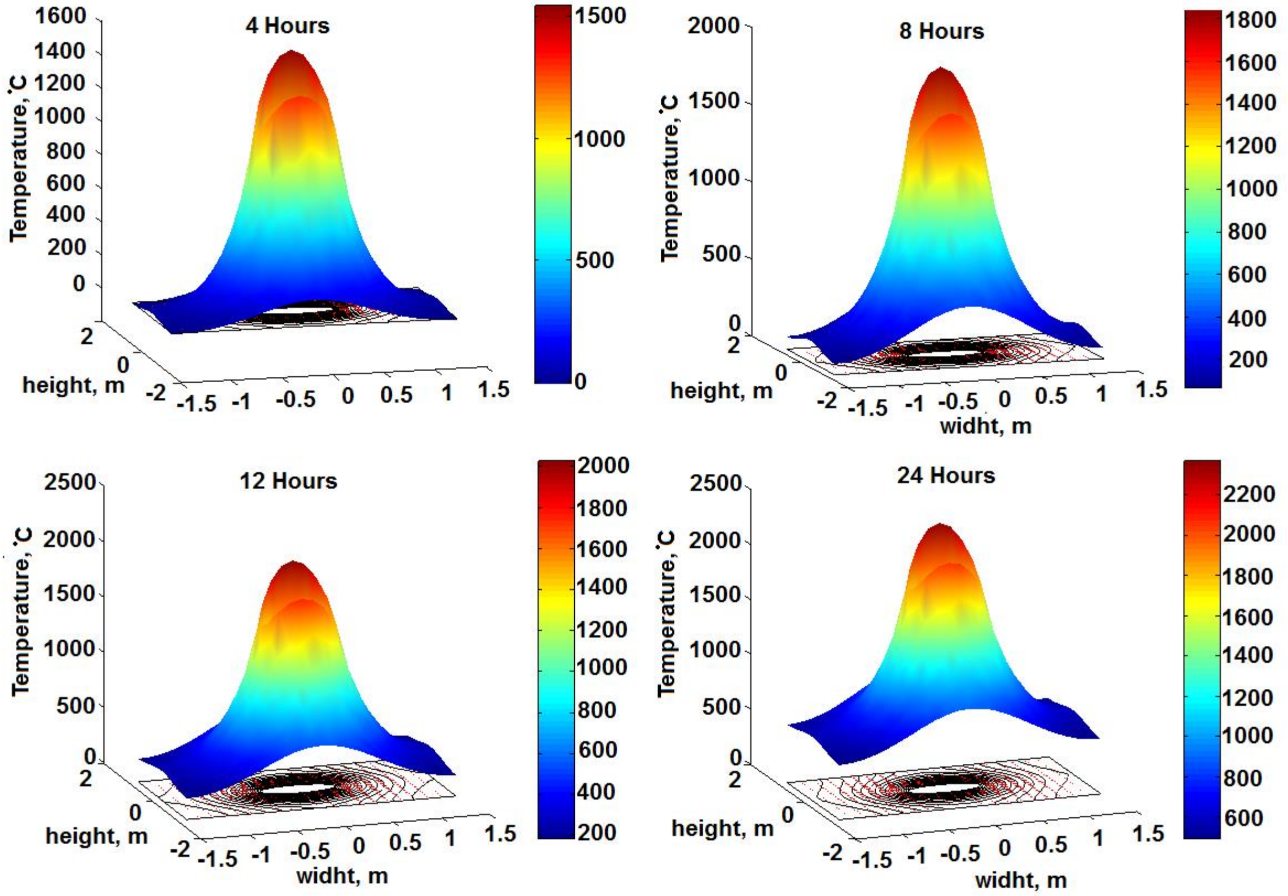

Figure 4: The distribution of the temperature field in the cross section of Acheson furnace after 4, 8, 12 and 24 hours of heating

1. Zone I - area of formation of intermediate products of silica reduction by carbon. Presented by siloxicon and aggregates containing 40-60 % SiC [7].
2. Zone II - amorphous area presented by crystals β - SiC (70-85 % SiC).
3. Zone III – macro-crystalline abrasive α - SiC (92-98 % SiC).

The 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 the 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.

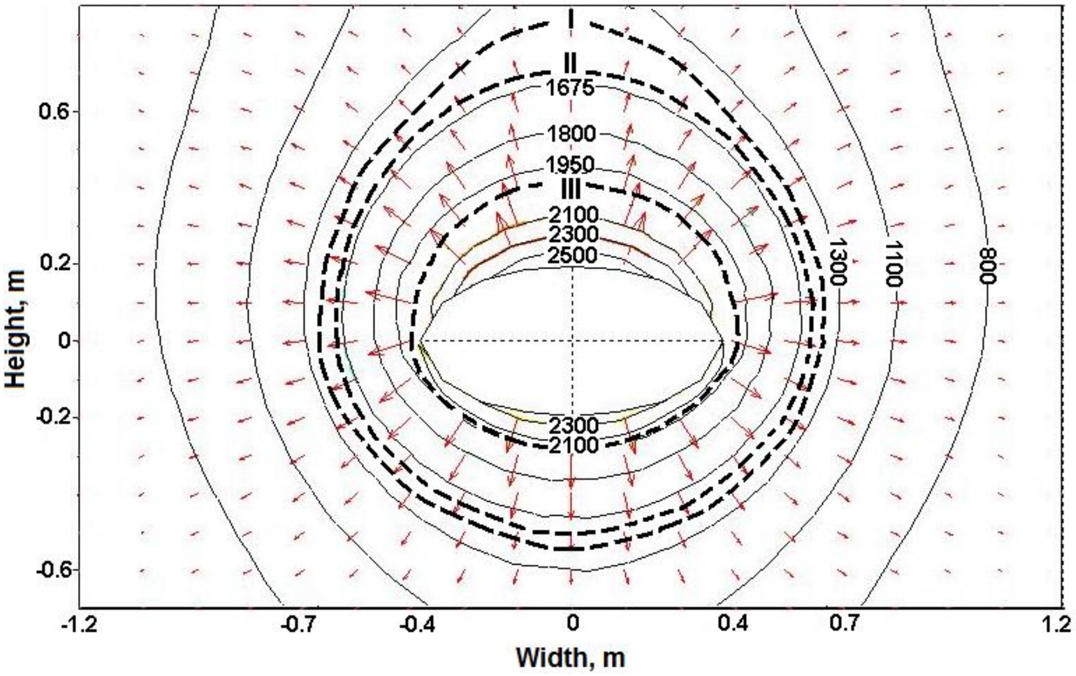

Figure 5: Figure 5. Temperature pattern distribution across the section of reaction zone of Acheson furnace after heating during 24 hours

CONCLUSIONS

1. Thermo-physical model of silicon carbide production process in Acheson furnace is developed. The dynamics of the thermal condition of the furnace reaction zone is computed by finite difference method with application of a PC.

2. The zones of existence of products of carbothermic reduction of silica are sized up by results of modeling.

3. It is reasonable to estimate the effect of input power dynamics on the sizes of zones of reduction products by means of a developed model in order to obtain analytical dependences of change of thermal condition of the furnace reaction zone which will enable the development of technological recommendations for thesilicon carbide production process and to develop Automatic Process Control System of the furnace.

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