

Integrated Process of Obtaining Heat and Silicon(IV) Oxide from Siliceous Plant Materials

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Abstract A differential thermal analysis of the process of preliminary prepared rice husk (PPRH) thermal treatment was conducted. The phase composition of the SiO₂ samples was investigated and the dispersed composition of SiO₂ and PPRH powders obtained as a result of PPRH thermal treatment was studied. The procedure mechanism and kinetic constants of the reactions of thermal transformation of PPRH into silicon(IV) oxide were offered. A mathematical model of the process of obtaining silicon(IV) oxide and thermal energy out of PPRH was developed which includes equations of the transformation kinetic of PPRH into SiO₂, heat and mass exchange and also equations of gas dynamics. The process was explored in the mathematical model.

Keywords Rice Husk, Thermal Energy, Silicon(IV) Oxide, Mathematical Model

1. Introduction

An important ecological problem in the whole world is environmental protection from waste matter, farming industry in particular.

One of such waste products is large-tonnage, constantly renewed waste of rice production – rice husk (RH). About 163 million tons of RH are produced annually in the world. Major countries of waste producers are China (41.27), India (29.41), Indonesia (14.17), Bangladesh (10.50), Vietnam (8.56), Myanmar (7.19), Thailand (6.92), Philippines (3.58), Brazil (2.78), Japan (2.33), Pakistan (2.27) and USA (2.20).[1,2]. Currently this type of farming industry waste treatment is a very important technical problem.

Considering RH as organic fuel we can talk about additional energy due to thermal effects that accompany the process of obtaining SiO₂. It can be considered that carbon and hydrogen contained in RH are the combustible part and SiO₂ is the cinder that is generated during the direct combustion of plant material [3,4].

Today, there are a sufficient number of RH processing methods with obtaining heat and SiO₂. It's known a method of obtaining silica from rice production wastes and device

for its implementation [5] which is conducted in the conditions of "clamped layer". The drawbacks of such method are: long period of burning of non-grinded RH, impossibility of providing of even process of combustion within the whole layer of raw material in the conditions of "clamped layer" that results into high carbon content of the final product.

Also there's known a method of obtaining silica and heat energy from plant siliceous wastes [6] which has such drawbacks as low efficiency and economy of obtaining the target product and heat owing to burning RH in the conditions of compact layer of raw material. In such conditions the diffusion of air, water and gaseous products of combustion through the layer of raw material decreases considerably and flows not even and as a result there occurs irregularity of temperatures through the whole length of the burning zone, the time of RH particles burning increases and the purity of the target product falls down. This method uses non-grinded RH that raises the time of its thermal treatment.

Therefore, this study aimed to developing method which will be considered and corrected these shortcomings.

2. Materials and Methods

With the help of elemental analysis the RH chemical composition was identified, % by weight: SiO₂ – 22.24, C – 35.77, O – 36.62, H – 5.2, N – 0.32 [7]. To study the process of co-production of silicon(IV) oxide and thermal energy PPRH was used. Depending on the method of RH preparation highly pure [8] or industrial silicon(IV) oxide can be obtained. In this work PPRH was rinsed with distilled water at the temperature 80-90°C, dried and grinded by a percussive-catotrical mill [9].

The PPRH heat treatment process was studied with differential thermal analysis (DTA) that was carried out on a derivatograph of «Paulik F.– Paulik J.– Erdey L.» system manufactured in Hungary. PPRH heat treatment was performed in an air atmosphere with the temperature range 20 - 1000°C at sample heating speed 10°/min.

To determine the phase composition of the products of PPRH thermal processing there was used X-ray diffraction

(XRD) that was carried out on a computerized diffractometer DRON-2 with upgraded collimation on the filtered $\text{CuK}\alpha$ -radiation.

To investigate changes in the particle size and dispersion of the PPRH powder during its heat treatment there was used the scanning electron microscopy (SEM) that allows to work in a wide magnification range from 10 to 1,000,000 fold. The survey was carried out using a scanning electronic microscope SEM-106I in secondary electrons with the boundary residual pressure in the microscope column (in the gun area) not more than $6.7 \cdot 10^{-40}$ Pa ($5 \cdot 10^{-6}$ mm. Mercury) and 111 mA gun current.

3. Results and Discussion

Figure 1 shows the results of the DTA. As we can see two endo- (120, 950°C) and two exoeffects (300, 450°C) are recorded on the DTA curve. The endothermic effect at 120°C is associated with the removal of free water from the PPRH. The exothermal effect at 300°C fixed on the DTA curve is caused by the combustion of cellulose and the exoeffect at 450°C – is caused by the process of lignin combustion [10,11]. Decomposition of PPRH ends at 800°C. The weight loss of the PPRH sample on ignition (LOI) is 78% by weight.

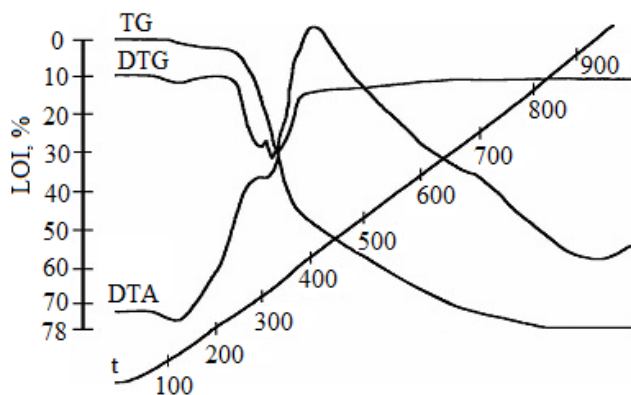


Figure 1. Derivation of PPRH

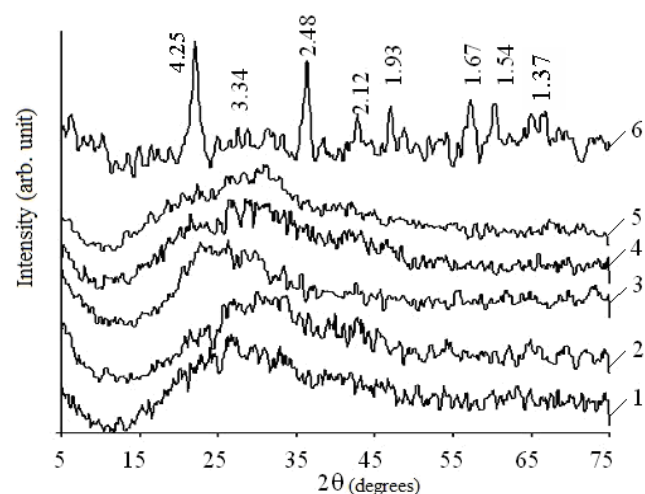
In Figure 2 we can see the X-ray diffraction patterns of SiO_2 samples obtained during PPRH heat treatment at different temperatures. It is clear that after PPRH ignition at temperatures from 500 – 900°C (lines 1 – 5) the SiO_2 samples are X-ray amorphous since the diffraction patterns of crystalline phase these samples diffraction peaks are not observed.

On the diffraction pattern of SiO_2 sample obtained after PPRH heat treatment at 1000°C (line 6) we can observe diffraction peaks at $d_{\text{HKL}} = 4.25, 3.34, 2.48, 2.12, 1.93, 1.67, 1.54, 1.37$ Å that correspond d_{HKL} for SiO_2 [12] that indicates the presence of crystalline phases in the sample.

Thus the exoeffect fixed at 950°C (Fig.1) indicates the transition of SiO_2 from an amorphous form to crystalline.

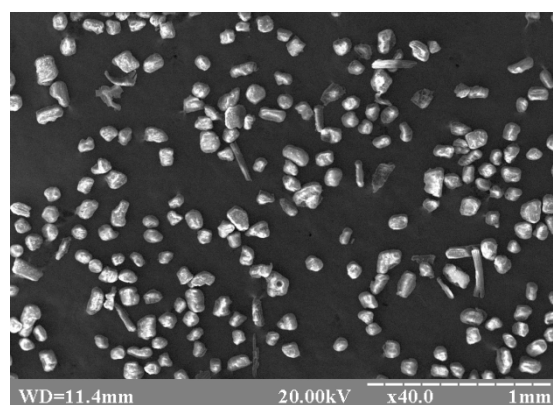
The change of PPRH particle diameter in the process of thermal treatment was determined by examining the photomicrographs of PPRH particles (Fig.3.a) and particles

of SiO_2 obtained by heat treatment of PPRH (Fig.3.b).

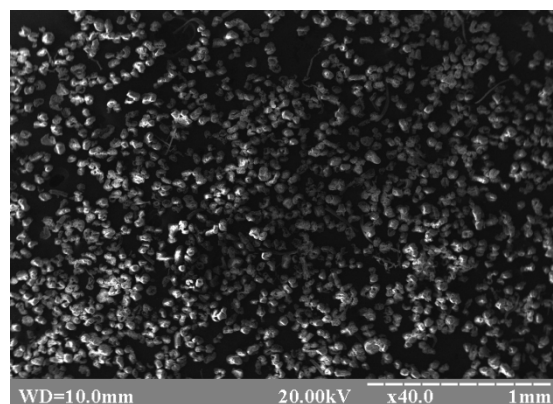


1 – 500, 2 – 600, 3 – 700, 4 – 800, 5 – 900, 6 – 1000.

Figure 2. XRD profiles for SiO_2 samples obtained from PPRH at different temperatures, °C:



a)



b)

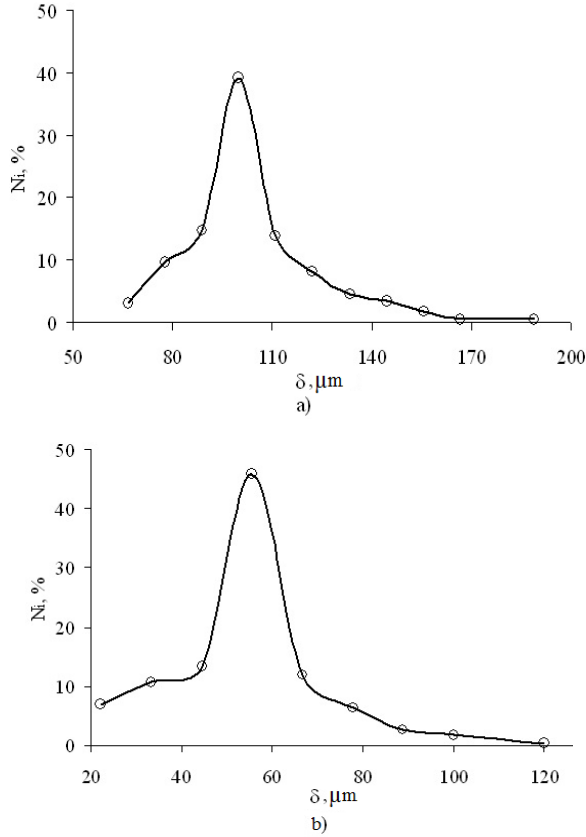
a – PPRH, b – SiO_2 obtained from PPRH

Figure 3. Powders photomicrographies

After processing the data derived from photomicrographs of PPRH and SiO_2 powders curves of PPRH and SiO_2 powders particle size distribution were constructed. Graphs shown in Figure 4. provide a visual representation of the

particulate composition of the powders of PPRH and SiO₂ obtained from PPRH.

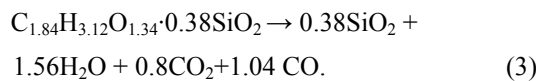
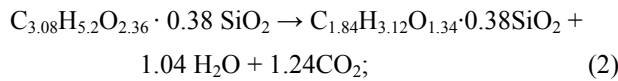
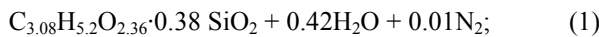
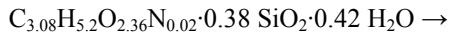
Figure 4 shows that in the studied sample of PPRH the biggest amount of particles are with diameter $\delta = 100$ microns the percentage of which (N_i) is 39.2% of the total particles counted and in the sample of SiO₂ the biggest amount of particles are with diameter $\delta = 55,6$ microns the percentage of which is 45,9%. Also, it can be concluded that the particles of PPRH vary in size ranging from 65 to 190 microns, and particles of SiO₂ range from 22 to 120 microns.



a – PPRH, b – SiO₂ obtained from PPRH

Figure 4. The curves of particle size distribution

After studying the data received during thermogravimetric, chemical and phase analyses of PPRH samples mechanisms of PPRH heat treatment reactions with obtaining silicon(IV) oxide were proposed:



As a result of DTA according to the methodology [13] there were calculated activation energy and pre-exponential factors of reactions (1) – (3) the values of which are given in Table 1.

Table 1. The values of activation energy and pre-exponential factors of PPRH heat treatment reactions

Chemical reaction	The pre-exponential factor, c^{-1}	The activation energy of the reaction, Joule/mol
1	$1.66 \cdot 10^3$	$39 \cdot 10^3$
2	$36.70 \cdot 10^6$	$102.97 \cdot 10^3$
3	$1.79 \cdot 10^1$	$56 \cdot 10^3$

On the basis of the proposed mechanism there were drawn 3 differential and 5 algebraic equations of the material balance of the PPRH heat treatment process [14]:

$$\frac{dn_1}{d\tau} = -k_1 n_1; \quad (1)$$

$$\frac{dn_2}{d\tau} = k_1 n_1 - k_2 n_2; \quad (2)$$

$$\frac{dn_3}{d\tau} = k_2 n_2 - k_3 n_3; \quad (3)$$

$$n_4 = 0,01n_1^0 - 0,01n_1 - 0,01n_2; \quad (4)$$

$$n_5 = 3,02n_1^0 - 3,02n_1 - 2,6n_2 - 1,56n_3; \quad (5)$$

$$n_6 = 1,04(n_1^0 - n_3); \quad (6)$$

$$n_7 = 3,08n_1^0 - 3,08n_1 - 2,92n_2 - 1,84n_3 - n_4 - n_6; \quad (7)$$

$$n_8 = 0,38(n_1^0 - n_1 - n_2 - n_3), \quad (8)$$

where k_1, k_2, k_3 are the rate constants of the corresponding chemical reactions, n_1^0 – the number of moles of PPRH at the initial time, n_i – the number of mol of i -th element involved in the reactions (1) – (3) at the current time.

The descriptions of components participating in the reactions (1) – (3) are shown in Table 2.

Table 2. The descriptions of components participating in the reactions of PPRH heat treatment

Component	Description
$\text{C}_{3.08}\text{H}_{5.2}\text{O}_{2.36}\text{N}_{0.02} \cdot 0,38\text{SiO}_2 \cdot 0,42\text{H}_2\text{O}$	n_1
$\text{C}_{3.08}\text{H}_{5.2}\text{O}_{2.36} \cdot 0,38\text{SiO}_2$	n_2
$\text{C}_{1.84}\text{H}_{3.12}\text{O}_{1.34} \cdot 0,38\text{SiO}_2$	n_3
N_2	n_4
H_2O	n_5
CO	n_6
CO_2	n_7
SiO_2	n_8

To develop a mathematical model of the combined process of obtaining heat energy and silicon(IV) oxide from PPRH there was proposed a physical model of the process

shown in Fig. 5.

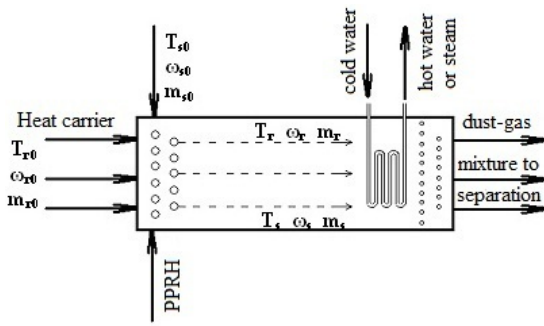


Figure 5. The physical model of the combined process of obtaining heat and silicon(IV) oxide from PPRH

The physical model is a cylindrical reactor, operating on the principle of a plug flow, wherein the PPRH heat treatment process is carried out in a moving stream of dust-gas mixture. According to the approved physical model, heat carrier with an initial temperature of T_{r0} , velocity ω_{r0} and mass flow m_{r0} is supplied into the initial section of the reactor, perpendicular to the flow of the heat carrier particles of PPRH with the initial temperature T_{s0} velocity ω_{s0} and mass flow m_{s0} are fed. The formed dust-gas mixture moves along the reactor where heat and mass transfer and chemical transformation processes take place. At the end of the heat treatment zone with a help of a heat exchanger, heat recovery of the dust-gas mixture is realized. After that the cooled mixture of dust and gas is separated into a solid target product SiO_2 and gaseous products of PPRH heat treatment.

When drawing up the mathematical model the following assumptions were made: the particles are spherical, their volume is negligibly small compared with the volume of the gas phase, the gas obeys the ideal gas law, heat exchange between the heat carrier and the dispersed particles takes place in adiabatic conditions, RH particle velocity in the initial section of the reactor is equal to zero [15].

The basic equations of the mathematical model of the combined process of obtaining heat and silicon(IV) oxide from PPRH to be considered:

The equation of particle motion

The equation of a particle motion is derived from the equations of motion of a solid sphere in a resisting medium [16]:

$$\frac{d\omega_s}{d\tau} = \frac{9f_x\mu_r}{2r_s^2\rho_s}(\omega_r - \omega_s), \quad (9)$$

wherein ω_r , ω_s – velocity of the heat carrier and the particles in the current section of the reactor, respectively; r_s – particle radius in the current section of the reactor; ρ_s – the particle density in the current section of the reactor; f_x – resistance function of the particle movement; μ_r – coefficient of dynamic viscosity of the heat carrier in the current section of the reactor.

The equation of particle heating

The equation of a particle temperature change was obtained by using the equation that describes the convective heat transfer between the particles and the heat carrier [17]:

$$\frac{dT_s}{d\tau} = \frac{3Nu\lambda_r}{2r_s^2\rho_s c_s}(T_r - T_s), \quad (10)$$

where T_r and T_s – respectively are the heat carrier and the particles temperature in the current section of the reactor; Nu – the Nusselt number that considers rarefaction of the heat carrier flow on the heat transfer rate; λ_r – coefficient of the heat carrier thermal conductivity in the current section of the reactor; c_s – thermal capacity of a particle in the current section of the reactor.

The equation of temperature change of the heat carrier flow

To derive the equation of fluid temperature change there was made up an equation of energy-conservation of the system:

$$\begin{aligned} m_{r0} \left(i_{r0} + \frac{\omega_{r0}^2}{2} \right) + m_{s0} \left(i_{s0} + \frac{\omega_{s0}^2}{2} \right) + Q_{\text{H}}^p + Q_{\text{add}} &= \\ = m_r \left(i_r + \frac{\omega_r^2}{2} \right) + m_s \left(i_s + \frac{\omega_s^2}{2} \right) \end{aligned} \quad (11)$$

where m_{r0} – is a mass flow rate of the heat carrier in the initial section of the reactor; i_{r0} – enthalpy of the heat carrier in the initial section of the reactor; ω_{r0} – heat carrier velocity in the initial section of the reactor; m_{s0} – mass flow of particles in the initial section of the reactor; i_{s0} – enthalpy of the particles in the initial section of the reactor; ω_{s0} – particle velocity in the initial section of the reactor; m_r , m_s – mass flow of heat carrier and particles in the current section of the reactor; ω_r , ω_s – velocity of the heat carrier and the particles in the current section of the reactor; i_r – enthalpy of the heat carrier in the current section of the reactor; $i_s = c_s T_s$ – enthalpy of the particles in the current section of the reactor; Q_{H}^p – the amount of heat released as a result of heat treatment of PPRH; Q_{add} – an additional amount of heat supplied to the system at the initial time.

In the temperature range 20 – 1000°C dependence of the heat carrier components enthalpy from the temperature can be approximated by the equation:

$$i_i = a_i + b_i T_r, \quad (12)$$

where a_i and b_i are coefficients of approximation for the i -th component of the heat carrier.

Mass flow of the particles and the heat carrier flow in the current section of the reactor can be expressed by the following equations:

$$m_s = m_{r0} W - \sum n_i M_i; \quad (13)$$

$$m_r = m_{r0} W + \sum n_i M_i, \quad (14)$$

where $W = m_{s0}/m_{r0}$ – the ratio of mass flow of PPRH particles and the heat carrier in the initial section of the reactor; n_i – mole number of the i -th gas component obtained

by the heat treatment of PPRH; M_i – the molecular weight of the i -th gaseous component; $\sum n_i M_i$ – the mass of gaseous products of the process of thermal decomposition of PPRH.

After substituting expression (12), (13), (14) into the equation (11) and differentiating it we obtain the equation of temperature change of the heat carrier flow:

$$\begin{aligned} \frac{dT_r}{dt} = & \frac{1}{(m_{r_0} + \sum n_i M_i) b_i} \left[\sum M_i \left(a_i + b_i T_r + \frac{\omega_r^2}{2} - c_s T_s - \frac{\omega_s^2}{2} \right) \frac{dn_i}{dt} + \right. \\ & + \omega_r (m_{r_0} + \sum n_i M_i) \frac{d\omega_r}{dt} + c_s (m_{r_0} W - \sum n_i M_i) \frac{dT_s}{dt} + \\ & \left. + \omega_s (m_{r_0} W - \sum n_i M_i) \frac{d\omega_s}{dt} - \sum Q_i \frac{dn_i}{dt} - Q_{add} \right] \end{aligned} \quad (15)$$

The equation of the heat carrier flow velocity

The expression for determining the rate of the heat carrier flow was derived from the heat carrier mass flow equation:

$$m_r = \rho_r \omega_r F, \quad (16)$$

where $\rho_r = \frac{1}{v_r}$ – is the density of the heat carrier (v_r – specific volume heat carrier) in the current section of the reactor; $F = \frac{\pi D_p^2}{4} = 0.785 D_p^2$ – the cross sectional area of the reactor; D_p – reactor diameter.

As a result of the conversion of the expression(16) we get:

$$\omega_r = \frac{m_r v_r}{0.785 D_p^2}. \quad (17)$$

After substituting the expression (14) into (17) and differentiating it we obtain the equation of the flow rate of the heat carrier:

$$\frac{d\omega_r}{dt} = \frac{1}{0.785 D_p^2} \left[(m_{r_0} + \sum n_i M_i) \frac{dv_r}{dt} + v_r \sum M_i \frac{dn_i}{dt} \right]. \quad (18)$$

The equation of the change in the specific volume of the heat carrier

The specific volume of heat carrier in accordance with the principle of additivity is found from the relation:

$$v_r = \sum v_i r_i, \quad (19)$$

where v_i , r_i – respectively are the specific volume and the mole fraction of the i -th component of the heat carrier in the current section of the reactor.

After differentiating the expression (19) we obtain the equation of the rate change of the heat carrier specific volume:

$$\frac{dv_r}{dt} = \sum v_i \frac{dr_i}{dt} + \sum r_i \frac{dv_i}{dt}. \quad (20)$$

The equation of the particle density change

When deriving the equation it is assumed that the particle density change during its heat treatment is due to burn out of

the volatiles and carbon from its volume. The equation for determining the particle density is:

$$\rho_s = \frac{m_q}{V_s}, \quad (21)$$

where V_s and m_q – are the volume and mass of a particle in the current section of the reactor respectively.

The equation for determining the particle volume is:

$$V_s = \frac{\pi \delta_s^3}{6}. \quad (22)$$

By substituting the equation (22) into (21) we get:

$$\rho_s = \frac{6m_q}{\pi \delta_s^3}. \quad (23)$$

The equation for finding the mass of the particle in the current section of the reactor is:

$$m_q = m_{q_0} - m_{\pi}, \quad (24)$$

where m_{q_0} – the mass of the particle in the initial section of the reactor; m_{π} – the mass of volatile components separated from a particle in the current section of the reactor in the process of its heat treatment.

$$m_{\pi} = \frac{m_{q_0}}{m_{s_0}} \left[n_1^0 M_1 - (n_1 M_1 + n_2 M_2 + n_3 M_3 + n_8 M_8) \right], \quad (25)$$

M_1 , M_2 , M_3 and M_8 – molar mass of components n_1 , n_2 , n_3 and n_8 .

The equation of a particle diameter change

After processing the data obtained during the study of photomicrographs of PPRH and SiO_2 samples (Fig.3) an equation for determining the particle diameter in the current section of the reactor was offered:

$$\delta_s = A + B m_{\pi}, \quad (26)$$

where A and B – are the coefficients of the approximation. The values of coefficients A and B depending on the primary particle diameter are shown in Table. 3.

Table. 3. The values of coefficients A and B depending on the primary particle diameter

The primary PPRH particle diameter, micron	$A \cdot 10^5$	$B \cdot 10^5$
50	5	-3,14
100	10	-6,5
150	15	-9,43
200	20	-12,65

The equation for determining the amount of heat of the system

$$Q = (Q_C n_C M_C) + (Q_H n_H M_H) + \sum (n_i M_i c_{p_i}) T_r + m_s c_{p_s} T_s, \quad (27)$$

where Q_C and Q_H – the heat of combustion of carbon and

hydrogen; n_C и n_H – the current number of moles of carbon and hydrogen; n_i и M_i – the current number of moles and the molar mass of the i -th gaseous component of the heat carrier; c_{p_i} and c_{p_s} – the current heat capacity of an i -th gaseous component and a particle respectively.

The heat capacity of a particle was calculated using the atomic heat capacity of elements in its structure:

$$c_{p_s} = \frac{n_C C_C + n_H C_H + n_O C_O + n_N C_N + n_{Si} C_{Si}}{n_C A_C + n_H A_H + n_O A_O + n_N A_N + n_{Si} A_{Si}}, \quad (28)$$

where $n_C, n_H, n_O, n_N, n_{Si}$ – the number of atoms of carbon, hydrogen, oxygen, nitrogen and silicon that form the particle; $C_C, C_H, C_O, C_N, C_{Si}$ – atomic heat capacity of carbon, hydrogen, oxygen, nitrogen and silicon respectively; $A_C, A_H, A_O, A_N, A_{Si}$ – atomic weight of carbon, hydrogen, oxygen, nitrogen and silicon respectively.

The system of equations included in the mathematical model was carried out in a software environment MathCad by BDF method (backward differentiation formula) based on the use of formulas of reverse differentiation and designed for solving stiff systems of linear and nonlinear differential equations.

Initial parameters specified were: W – the ratio of the mass flow of particles to the mass flow rate of heat carrier supplied to the initial section of the reactor; T_{s0} and T_{r0} – the initial temperature of the particles and the heat carrier; w_{s0} и w_{r0} – the initial velocity of the particles and the heat carrier respectively; ρ_{s0} и δ_{s0} – the initial density and diameter of a particle; v_{cm} – specific volume of the heat carrier components mixture; D_p – the diameter of the reactor.

Boundary conditions set were: the starting time $\tau_0 = 0$ sec.; the end of calculation – when the equality (29) is realized:

$$n_{SiO_2(i)} - n_{SiO_2(i-1)} = 10^{-3} \text{ moles}, \quad (29)$$

where $n_{SiO_2(i)}$ – is the number of moles of SiO_2 on the i -th step of integration; $n_{SiO_2(i-1)}$ – the number of moles of SiO_2 in the previous step of the integration.

Solving the system of equations (1) – (27) there yielded relations of distribution of concentrations of the PPRH system components – the heat carrier in time (Fig.6) and influence of the mass ratio PPRH/heat carrier (Fig.7) on the amount of the heat energy of the system in the process of heat treatment of PPRH.

From Figure 6 it is clear that the process of transformation of PPRH into silicon(IV) oxide has 3 stages. The first stage proceeds with decomposition of PPRH and generating n_2, n_4 and n_5 . At the second stage – decomposition of n_2 takes place forming n_3, n_5 and n_7 . At the third stage, n_3 dissociates generating a solid target product n_8 and gaseous n_5, n_6 and n_7 .

With the increase of the initial temperature of the heat carrier from 600°C (Fig.6.a) to 1000°C (Fig.6.b) the time of a complete transformation of PPRH into SiO_2 decreases from 1900 to 240 seconds and the temperature of a particle reaches its maximum value of 520 and 830°C respectively.

From Figure 7 it is clear that at the change of weight ratio

of RH/heat carrier from 1/2 to 1/10 the amount of thermal energy of the system remains constant and equal to 16 MJ/kg of RH. When changing the mass ratio of RH/heat carrier in said changing within a heat release rate in accordance with the pattern of RH thermochemical conversion.

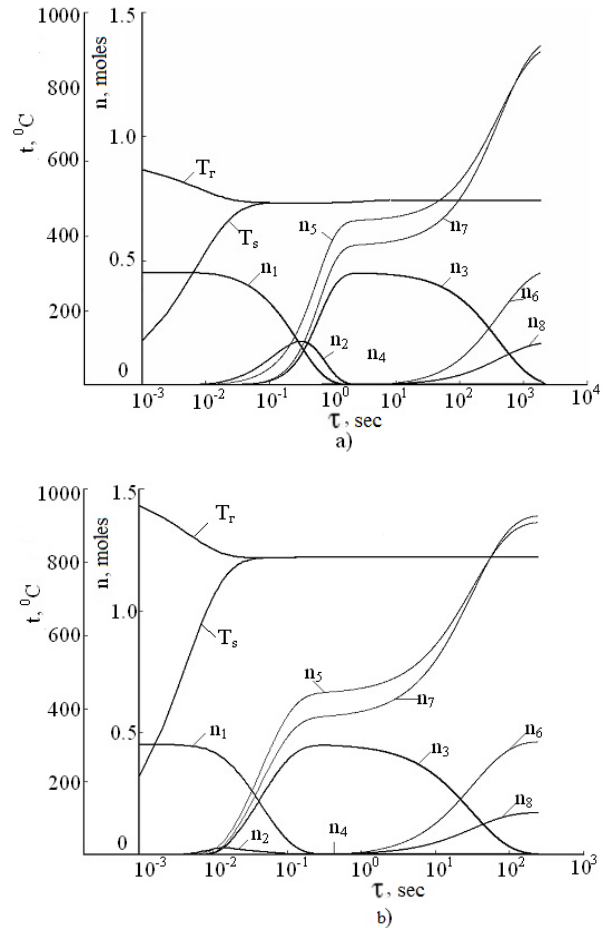


Figure 6. The dependence of the concentrations distribution of components of the PPRSH – heat carrier system in time at $W = 1/5, \delta_{s0} = 50 \mu m, ts_0 = 27^\circ C, ws_0 = 0 \text{ m/sec}, D_p = 0,4 \text{ m}, tr_0 = 600$ (a), $tr_0 = 1000^\circ C$ (b)

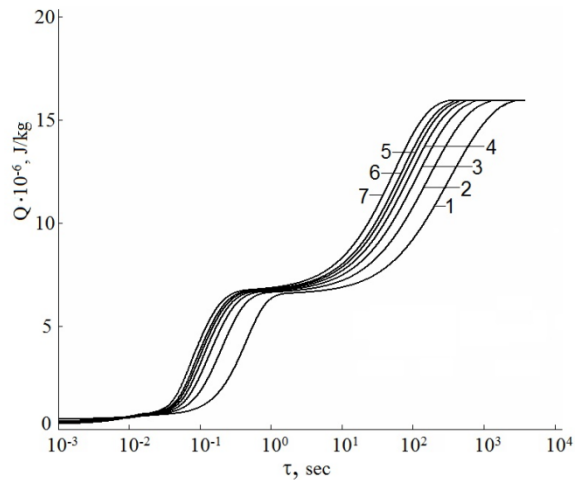


Figure 7. The change of the amount of heat energy during the heat treatment of PPRH in time at $\delta_{s0} = 50 \mu m; ts_0 = 27^\circ C; ws_0 = 0 \text{ m/sec}; D_p = 0,4 \text{ m}, tr_0 = 800^\circ C, W = 1/2$ (1); $1/3$ (2); $1/4$ (3); $1/5$ (4); $1/6$ (5); $1/7$ (6); $1/10$ (7)

4. Conclusions

1. A differential thermal analysis of the process of PPRH heat treatment was carried out and pre-exponential factors and activation energies of reactions of PPRH thermal transformation into silicon(IV) oxide were calculated.
2. Using XRD analysis of SiO₂ patterns obtained from the heat treatment of PPRH at various temperatures, phase composition were studied, and it was defined that when carrying out the process of PPRH heat treatment in the temperature range of 500 - 900°C, the obtained product is amorphous. When carrying out the process of PPRH heat treatment at a temperature above 1000°C the obtained product has a crystalline structure.
3. After studying the photomicrographs of PPRSH particles and particles of SiO₂ obtained by PPRH heat treatment it was found that the particle diameter decreases in the range of 45 - 50% of its initial diameter.
4. A mechanism of the process of thermal transformation of PPRH into silicon(IV) oxide was offered, and based on this mechanism equations of the chemical kinetics of the process were compiled.
5. A mathematical model of the a combined process of obtaining heat and silicon(IV) oxide was developed involving the equations of heat and mass transfer, gas dynamics and the equations of chemical kinetics of the process.
6. It was defined that when increasing the initial temperature of the heat carrier from 600 to 1000°C with all other conditions being equal the time of a complete transformation of PPRH into SiO₂ decreases from 1900 to 240 seconds. As we can see from Figure 6. a. b. out of 0.452 moles of PPRH it's produced 0.171 moles of SiO₂ which is equivalent to 0,205 kg SiO₂ out of 1 kg of PPRH.
7. It was established that when the weight ratio of RH / heat carrier changes from 1/2 to 1/10 the amount of heat energy released during the heat treatment of PPRH is 16 MJ / kg of PPRH.

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