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Mathematical Modeling of Heat Transfer Processes in a Layer of Moving Coked Particles

Mikhail Zhumagulov, Madina Yerkalina, Samal Sadykova

Power Engineering Department, Transport, and Power Energy Faculty, L. N. Gumilyov Eurasian National University, Republic of Kazakhstan

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Abstract

The article presents mathematical and experimental studies of the coal layer subjected to thermal-oxidative coking on a moving chain-grate – a direct drive conveyor for the coal that doesn't coke in traditional coke oven batteries. A physico-mathematical model of the temperature field in the coking layer has been developed. A comparison of the model with the existing analogues has been made. The model was tested on operating installation. The main operating parameters of the installation, such as bed temperature and coking period, were obtained for the most efficient mode.

Keywords: *Thermal-oxidative coking; Coke; Semi-coke; Grate-fired furnace; Heat transfer; Temperature field.*

1. Introduction

The process of thermal-oxidative coking allows obtaining special types of coke from solid fuels which can be used for smelting of calcium carbide in electric furnaces, as well as for the production of ferroalloys, phosphorus and ore sintering; used as a smokeless fuel and in some chemical processes.

The idea of coking in the chain grate conveyor first appeared and was implemented at the factory of Shawinigan Chemicals (Canada) in 1938. The principal difference of this method of obtaining a reducing agent from traditional coke batteries lies in high heating rates, which makes it possible to obtain a reducing agent from low-caking non-deficient types of coal, which significantly expands the coal base of coke production.

Thermal-oxidative coking is carried out by high-speed heating of coal particles or granules on a direct drive chain grate conveyor. The required amount of heat is provided by burning the lower layers of the coal load adjacent to the fire-bar (no more than 10% of the total mass of coal), as well as the volatile matter in coking coal that is burned in the overlayer space of the combustion chamber. Of course, part of the volatile matter starts burning in the layer, but experimental studies revealed that internal sources of heat in this process represent a small fraction of the total heat flux and therefore they can be neglected to simplify the conclusions in the proposed model.

The study of D. Mendeleev University of Chemical Technology of Russia identified the possibility of this process implementation in the direct drive chain-grate stoker. The use of energy boilers greatly simplifies the adoption of the method in the national economy and allows combining the processes of generation of thermal energy and technological product (coke). Air for combustion of coal is supplied by blowing fans at the controlled quantities which allows avoiding a noticeable burning out of solid carbon. Direct contact of the combustion products with individual pieces of coal ensures high heating rates and, as a result, high specific productivity of the process.

2. Technological process description

In order to study the process, the authors chose a modernized grate-fired furnace of the KVTS (Solid Fuel Water Boiler)-20-150 boiler of the Aksu Ferroalloy Plant. The basic technological installation scheme is shown in Figure 1. The fuel was low-grade coal from the Shubarkol deposit of the Karaganda region with the heating value Q_r^i = 21453 kJ / kg. The considered energy-technological process, which takes place in the furnace of the boiler, is an incomplete combustion process, which consists in heating graded coal on the conveyor belt *4*. The required amount of heat is provided by burning the volatile matter of the coked coals. In the radiant heat part of the installation the coal loading layer is dried, heated and ignited in the temperature zone of 850–1100°C, which is sufficient to completely or partially remove the volatile components of the coal. The air for combustion of coal is supplied by a fan through the wind box 6 from under the grill in strictly controlled quantities, which makes it possible to avoid noticeable burning out of solid carbon. The air for combustion of coal is supplied by a fan through wind box *6* from the stoker at strictly controlled quantities, which makes it possible to avoid noticeable burning out of solid carbon. Direct contact of the combustion products with individual pieces of coal provides high heating rates and, as a result, high specific productivity of the coke formation process.

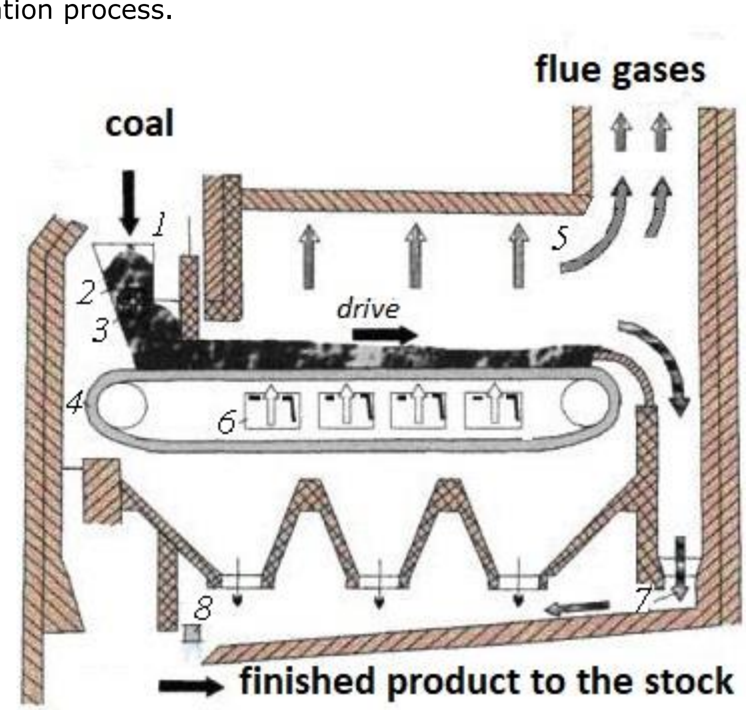

Figure 1 - Technological scheme of the installation
1- raw coal bunker; *2*- coal; *3*- mechanical spreader; *4*- conveyor belt; *5*- combustion chamber; *6*- wind box; *7*- reducing agent; *8*- water quenching

The presence of two end products makes the coking process in the chain grate conveyor particularly valuable for industries that consume both thermal energy and coke for special purposes.

The transition from complete to incomplete combustion is implemented by the following measures:

1. *An increase in the movement velocity of the grate* (compared to the nominal combustion mode) at constant blow rates and bed height leads to a lengthening of the ignition zone and the zone of formation of the reducing agent, and, consequently, to an increase in the incomplete mechanical combustion;

2. *An increase in the layer thickness* at a certain lattice length and constant speeds of blast and conveyor belt movement leads to the spread of the ignition zone towards the end of the lattice, which also leads to increased mechanical incomplete combustion;
3. *Restricting the air supply*, especially in the last zones of the furnace, leads to a reduction zone stretching along the length of the lattice.

3. Heat and material balance

Initially, the calculation of the heat balance of the installation was made by analogy with the heat balance of a typical boiler [8], but taking into account the technological features of the machine:

1. During the heat treatment of coal, only the carbon fraction of the fuel burns (no more than 10% of the solid residue). According to this value, *q3* can be neglected, due to the fact that the value of *q3, when converted to 100% of the mass of fuel,* is too small;
2. The studied energy technological process of obtaining thermal energy in the form of hot boiler water and special types of coke implies the release of the technological product, as a result of the mechanical incomplete combustion of the source material (coal). Therefore, one of the main tasks is to maintain the *q4* loss value at a level close to the carbon content of the fuel. As a result, *q4* is calculated using the formula (1) based on the material balance of the coking process [14]:

$$Q_4 = (1-x)\cdot\left(\frac{100-(W^r+A^d)}{100}\right)\cdot\left[1-\frac{\left(V_H^{daf}-V_K^{daf}\right)}{100}\right]\cdot Q_i^r\,, \qquad (1)$$

where (1– x) – coefficient considering the proportion of carbon burned x; W^r – fuel moisture on the working mass, %; A^d – the ash content of the fuel on a dry basis, %; V_H^{daf}; V_k^{daf} – yield of volatile substances in the initial fuel and residual - in the coke on the dry ash-free mass; %; Q_i^r – lower heating value of the solid fuel, kJ/kg.

The result of the heat balance of the installation for the production of special types of coke based on typical hot-water boilers KVTS (Solid Fuel Water Boiler) -20-150 is presented in Table 1.

Table 1. Heat balance of a carbonaceous reducing agent plant

Name	Dimension	Value
Asset side:		
Lower heating value of the solid fuel, Q_i^r	kJ/kg	21453.7
Heat brought in a fire chamber with air, Q_B	kJ/kg	0
Expenditure side:		
Actual working thermal load of the installation, Q_1	kJ/kg	40134791
Feedwater consumption, *D*	*kg/h*	239125.3
Reduced heat loss from mechanical incomplete combustion, q_4	%	45.2
Heat loss with outgoing combustion products, q_2	%	3.69
Heat loss from chemical incomplete combustion, q_3	%	0
Loss of heat to the environment, q_5	%	4.17
Thermal efficiency of the unit, η_a	%	46.93
Estimated fuel consumption, $B_т$	*kg/h*	3986.07
Actual air flow per unit, $V_Д$	*m³/h*	26251.55
Loss in yarn, *x*	%	9.91

According to the results of the calculation of the heat balance of the installation [8], the calculated air consumption V_D, water consumption *D* and fuel consumption $B_т$ was determined for the conditions of thermal-oxidative coking. Then we should verify the calculated indexes experimentally.

4. Physico-mathematical model of the temperature field

To characterize the thermal conditions of coking, the information on the temperature field by the geometrical coordinate and the features of its change with time from the moment of the end of the furnace feed loading to the completion of the process of obtaining the reducing agent is of considerable interest.

Obviously, the development of a detailed mathematical description of all processes in the coal loading volume (heat transfer from combustion products to coal grains and between grains, chemical degradation and synthesis reactions involving various organic matter ingredients, formation and thermolysis of plastic mass, product formation at various stages from semi-coke to lump coke) is not possible due to the complexity of their description.

The greatest attention in the literature is given to one-dimensional mathematical models of the furnace chamber [8-11], when its temperature field seems to be symmetrical about the axis, i.e., under averaged thermal conditions over the entire width of the chamber.

The layer of granular materials is characterized by the presence of two phases - solid in the form of particles of material and gaseous, filling the pores between the particles and sometimes pores inside the particles. The surface of the particles serves as the boundary between the phases. Physico-chemical processes in the layer can occur both in the space between particles (homogeneous reactions) and on the surface of the phase separation (heterogeneous reactions). In thermo-oxidative coking processes, the latter type of reactions is crucial (carbon combustion, moisture evaporation). An example of homogeneous reactions is the burning of CO to CO_2 in the pores between the fuel particles.

The processes of heat and mass transfer can develop inside individual particles (internal task) and on their surface (external task).

In the case of heat conduction, not complicated by diffusion, the temperature values at different points in time and at different points of the body are found from the solution of the Fourier differential equation. Using the similarity theory, for the case under consideration it is written in the form

$$\frac{\partial\theta}{\partial Fo} = \nabla^2\theta, \qquad (2)$$

where F_o – the Fourier criterion; ∇^2 – the Laplace operator; θ – dimensionless temperature.

Consider the process of heat transfer when filtering a gaseous heating fluid through a layer of lump material. In this case, the main amount of heat is transferred to individual particles of the material by convection; the amount of heat transferred by heat conduction between particles, as a rule, is small and can be neglected in the overall heat balance. The role of radiation during convective heating of the layer is also significant due to the relatively high process temperatures (about 1000°C), despite the small size of the channels between the lumps and low concentrations of triatomic gases. Consequently, the heat transfer coefficient from gases to the layer of solid dispersed material α_v, in this case, will be a certain equivalent coefficient characterizing the joint transfer of heat by convection and radiation.

Direct contact of the combustion products and material particles, as well as the highly extended surface of the particles, ensure effective conditions for heat exchange with the uniform motion of gases through the bed without disturbing its stability. In practical terms, lumpy material layer consists of particles of different sizes. The mathematical solution of the heat transfer problem in such a polydisperse layer is greatly complicated. Therefore, we average the size of the material particles, i.e., we replace the real layer with a fictitious one consisting of spherical particles of the same equivalent diameter d_e. In a first approximation, the averaging can be carried out according to the formula of the average diameter by weight:

$$d_e = \sum g_i \cdot d_i, \qquad (3)$$

where g_i – the share of i – th fraction.

Schematically, the heat exchange process in the layer at cross-current is shown in Fig. 2. When heat exchange is performed according to the cross-current pattern, there is no relative movement of the material particles, and the layer moves as one unit. The displacement of the layer x is related to the duration of the process τ by the relation:

$$x = L = w \cdot \tau, \qquad (4)$$

where w – layer motion rate.

The temperature of the gas and material during heat exchange in a cross-flow pattern is a function of two independent variables: y and x or y and τ.

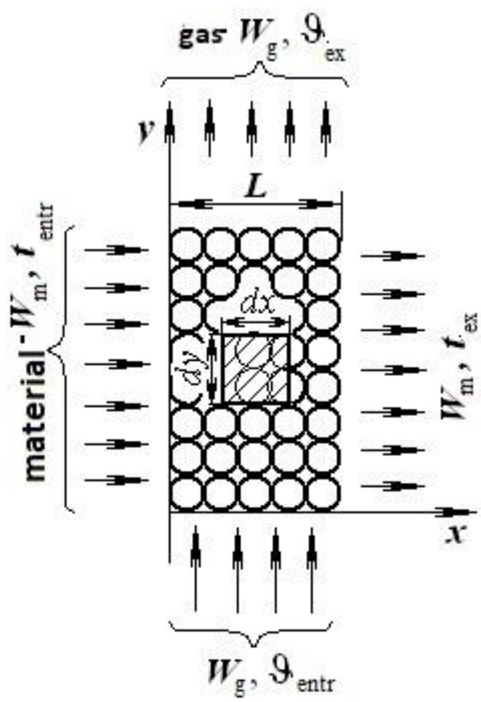

Figure 2. Scheme of heat exchange process in the layer of lump material

The process of heat transfer in the layer of real lumpy materials is determined both by the heat exchange between the gas and individual particles of the material, and the heat distribution in the particles themselves. Joint consideration of these two factors significantly complicates the task. Let us assume that the thermal resistance of particles R does not limit the process, i.e. $R/\lambda_t > 0$ (where λ_t is the thermal conductivity of the heat-treating material at temperature t).

To derive the differential heat transfer equations, we select the elemental volume $dV=dx \cdot dy \cdot dz$ in the layer and consider the change in the enthalpies of the material and gas as the latter passes through this element (the material is heated in a steady state).

The heat-transfer gas, passing through the selected element of the layer, transfers part of the heat to the material

$$dQ = \alpha_v \cdot (\vartheta - t) \cdot dV. \quad (5)$$

As a result of the heat transfer, the enthalpy of gas and material will change:

$$dQ = Q_i^{vg} \cdot w \cdot \frac{\partial m}{\partial y} \cdot dV - c_g \cdot w \cdot \frac{\partial \vartheta}{\partial y} \cdot dV, \quad (6)$$

and

$$dQ = (1 - n) \cdot c_m \cdot \rho_m \cdot \frac{\partial t}{\partial \tau} \cdot dV, \quad (7)$$

where ∂m – mass loss in volume dV; n – average porosity; Q_i^{vg} – the lower heating value of volatile gases.

The first member of the right side of equation (6) describes the internal source of heat associated with the burning of volatile substances inside the layer.

Based on the energy conservation law, we equate equations (5) and (6), (5) and (7) and after transformations, we obtain a system of differential equations that determine the change in gas and material temperatures in the layer:

$$\frac{\partial \vartheta}{\partial y} = \frac{Q_i^{vg}}{\bar{c}_g} \frac{\partial m}{\partial y} - \frac{\alpha_v}{\bar{c}_g \cdot w_g} \cdot (\vartheta - t) \quad (8)$$

$$\frac{\partial t}{\partial \tau} = \frac{\alpha_v}{(1-n) \cdot \bar{c}_m \cdot \rho_m} \cdot (\vartheta - t) \quad (9)$$

Before solving differential equations (8) and (9), we note that they will also be valid for real heating of the pieces of finite thermal conductivity (if $R/\lambda_t \neq 0$) if the internal thermal resistance of the material particles is known . Then the heat transfer coefficient α_v can be given the value of total heat transfer coefficient k_v, which considers both the external and internal thermal resistance of the material particles. According to experimental data [8], it was found that the heat transfer coefficient k, which considers both external and internal thermal resistance of the material particles, can be expressed for spherical particles in the form:

$$k = \frac{\alpha}{1 + \frac{1}{5} \cdot Bi}, \quad (10)$$

where Bi – Bio criterion.

After mathematical transformations we obtain:

$$\frac{1}{k_v} = \frac{1}{a_v} + \frac{d_e^2}{15 \cdot (1-m) \cdot \lambda_t}, \quad (11)$$

Thus, equations (8) and (9) with a sufficient approximation can be used to find temperature fields in the layer of real materials, if we calculate by the total heat transfer coefficient:

$$\frac{\partial\vartheta}{\partial y}=\frac{Q_i^{vg}}{\bar{c}_g}\frac{\partial m}{\partial y}-\frac{1}{\frac{1}{\alpha_v}+\frac{d_e{}^2}{15\cdot(1-n)\cdot\lambda_t}}\frac{1}{\bar{c}_g\cdot w_g}\cdot(\vartheta-t) \quad (12)$$

$$\frac{\partial t}{\partial\tau}=\frac{1}{\frac{1}{\alpha_v}+\frac{d_e{}^2}{15\cdot(1-n)\cdot\lambda_t}}\cdot\frac{1}{\bar{c}_m\cdot\rho_m}\cdot(\vartheta-t) \quad (13)$$

The **boundary conditions** that allow solving the system of equations (12) and (13) are as follows:

1. Specific heat capacity $c_м$ and thermal conductivity $\lambda_м$ for each given point are substituted according to the temperature dependences given in [15].
   The temperature dependence of the volumetric heat capacity of the flue gases of the average composition [11] with sufficient accuracy (δ < 3 %) can be described by the following expression:

$$c_g = (0{,}8 \cdot 10^{-3} + 0{,}2 \cdot 10^{-5}\cdot t_l)^{-1}. \quad (14)$$

2. When taking into account, the heat released or absorbed as a result of chemical reactions during coking of the furnace feed, in the right-side side of equation (13) one should add an addend describing heat fluxes from exo- or endothermic sources. Expressions in the form of a polynomial for calculating the thermal effect were obtained in [15].
3. At any time, the temperature change in the space of $t(y, \tau)$ occurs only in the y-direction perpendicular to the surface of the coal layer. The heat and mass transfer along the x coordinate at each separate moment of time can be neglected since the movement velocities along the x and y coordinates are incommensurable.
4. At the initial moment of time, the coal layer has a uniform temperature distribution (30°C) throughout the entire volume of coal:

$$t(y, 0) = 30°\text{C},\ 0 \le y \le h; \quad (15)$$

i. e.

$$dt/dy = 0, \text{ when } \tau = 0. \quad (16)$$

5. The temperature of the heating gases in the plane of the entrance to the coal layer is assumed to be equal to the calculated combustion temperature of coal $t_г$:

$$\vartheta\ (y_{entr}, \tau) = t_г,\ 0 \le \tau \le \tau_{ex}; \quad (17)$$

i. e.

$$d\vartheta/d\tau = 0, \text{ when } y = y_{entr} \quad (18)$$

6. The temperature of heating gases in the plane of exit from the coal layer is taken according to experimental measurements of the temperature of the furnace space ($t_г'$=1000°C) at the height of 1 m from the hearth:

$$\vartheta\ (y_{ex}, \tau) = t_g',\ 0 \le \tau \le \tau_{ex}; \quad (19)$$

i. e.

$$d\vartheta/d\tau = 0, \text{ when } y = y_{ex}. \quad (20)$$

The solution of the system of equations was performed using a computer (programming language - Quick Basic) by the method of finite-difference approximation of the initial system of differential equations with given grid dimensions [13].

To simulate the heat transfer of the coal layer with a height of 0.2 m, the calculated area equal to the layer height minus the loss in the yarn of carbon x was divided into 20 cells, each of which corresponded to 0.01 m. Such a partitioning of the working grid can be considered optimal since, with further fragmentation in the calculation process, an accumulation of rounding errors occurs, and the accuracy of the calculation does not significantly increase. Such a partitioning of the working grid can be considered optimal since, with further fragmentation in the counting process, an accumulation of rounding errors occurs, and the accuracy of the calculation does not significantly increase. The time step was 0.00726 h, that is, with a coking period of 0.726 h, the number of nodes in the time coordinate reached 100.

Table 2. The quality of coal from the Shubarkol mine by size class

Stage	Coal class	Particle size distribution, %					Average size of the lump	Technical analysis, %		
	mm	> 40	40-20	20-10	10-5	5-0	*mm*	W^r	A^d	V^{daf}
I	50-150	41.5	36.5	12.1	6.2	3.7	34.1	10.1	2.9	42.9
	max.	61.3	44.9	16.5	7.6	7.8		12.1	3.5	44.8
	min.	30.5	25.8	6.5	4.8	1.6		94	2.5	41.8
II	25-50	26.4	52.4	12.4	5.3	3.5	31.3	8.5	3.1	42.1
	max.	33.8	61.2	21.4	12.8	8.6		10.5	3.6	43.1
	min.	15.7	44.3	4.6	3.0	1.5		5.8	2.0	40.5

Data on furnace feed and thermal mode of coking corresponded to the actual production conditions (Table 2):

- The lower calorific value of volatile substances of fuel $Q_i^{гп}$ = 17695.94 kJ/m^3
- Calculation of the calorimetric temperature of burning fuel is carried out by the method of successive approximations [15]. Next, the actual temperature was determined as the product of the calorimetric temperature and the pyrometric coefficient. As a result, the temperature $t_г$ =1167°C was obtained.
- Porosity is calculated by the formula:

$$n = 1 - \frac{\rho_b}{\rho_m}. \tag{21}$$

where $\rho_н$ – bulk density; $\rho_м$ – material density;

- Equivalent diameter according to the formula (21) on the basis of the sieve composition given in Table 2 with possible further refinement:

$$d_e = \sum g_i \cdot d_i. \tag{22}$$

The result of the calculation of the temperature field of the coal layer in the furnace of unit 7 of the Aksu Ferroalloy Plant is presented in Fig. 3, which shows the temperature change over the period of coking at various points along with the layer height (y = 0.018–0.2 m). Intermediate temperature curves correspond to cells that are 0.01 m behind each other.

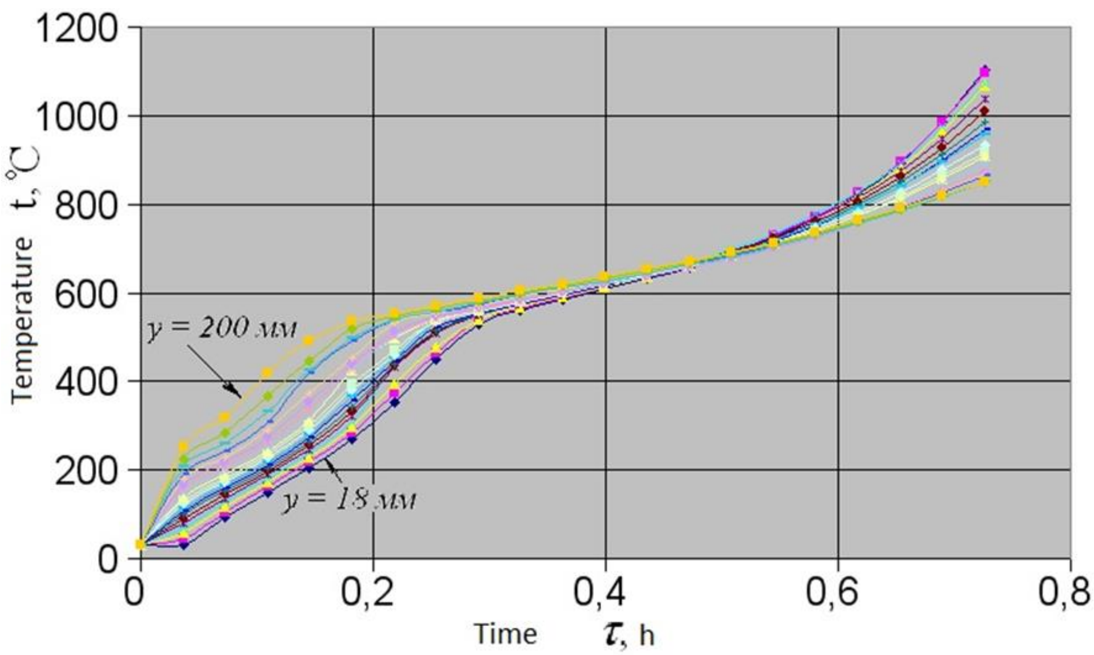

Figure 3. The results of the carbon bed temperature field simulation

At the beginning of the process, in each loading layer, the temperature of the material rises rapidly, which mainly accounts for the first quarter of the grate and partly on the second. Then the intensity of the temperature rise slows down. At the end of the second and third zones, the stage of low-temperature coking proceeds at a temperature of 600-800°C. In the last zone, towards the end of the coking period, there is again an intense increase in temperature throughout the layer due to an increase in the thermal conductivity of the carbonized material and structure reaction of semi-coke and coke.

When comparing the obtained temperature field with the data of studies by other authors [9, 11], in general, there is a similar nature of the curves. The only difference is in the specific duration of the stage of smooth temperature increase, since the analogs investigate the fields of the stationary furnace feed layer, and in our case there is a continuous movement of the grate, as a result of which the area of low-temperature coking is lengthened.

It should also be noted that the nature of the temperature curves is consistent with industrial test data.

5. The methodology of the experiments

When assessing the adequacy of the model of the installation under consideration, that is, when comparing its results with experimental data, it should be taken into account that reliable monitoring of temperatures throughout the chamber when operating the installation with a chain grate is a rather difficult technical task due to the continuous movement of the chain grate and coal layer with it. In this regard, it was decided to measure the temperature in the layer depending on the length of the coal layer, and not on time. Typically, in practice, it is possible to trace the transformations of the temperature field in the coked load with any degree of reliability only in a small number of positions, usually in a certain section of the chamber [16]. Thus, during the examination of the studied energy-technological units at the Aksu Ferroalloy Plant, temperature field measurements were made in the chamber section along the length by lowering probes (stainless steel pipe covers) with thermocouples of chromel alumel type (CAT) to a depth of 0.1 m, as well as constant measurements taking from four CAT thermocouples mounted at a height of 1 m from the bottom. A probe with a thermocouple immersed in the layer through an observation window mounted from the front of the installation. The results of the experimental measurements are shown in Figure 4.

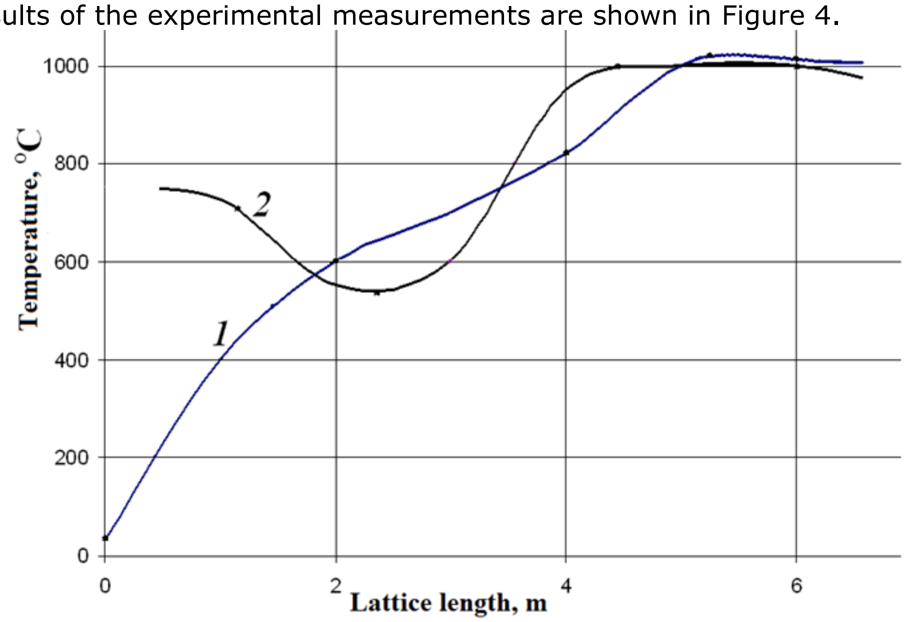

Figure 4. Temperature distribution along the lattice length; *1* - in the layer at a depth of 0.1 m (with a loading layer thickness of 0.2 m); *2* - in the furnace space at a height of 1

When fitting the calculated and experimental curves, it is possible to draw the following conclusion:

- in general, the nature of the simulated curves corresponds to the current processes taking place during thermal oxidative coking. The maximum deviation is 6.6% in the plane of 3.7139 m or 0.4145 hours.
- the readiness of the reducing agent for dispensing is usually controlled upon reaching temperature of about 1000°C on the axis. The calculation according to the installation model showed that when the coking period is τ = 0.726 h and the grate speed is 8.96 m/h, the temperature of individual layers of the reducing agent in the last zone reaches 850-1100°C, which does not contradict the experimental data on the chain grate installation of the Aksu Ferroalloy Plant during production testing of the furnace feed from the Shubarkol deposit coal. From the above analysis follows the possibility of increasing the grate speed up to 9 m/h.

To control the burning out of volatile substances, samples of coal were taken from different zones of the lattice, and the temperature in the coal layer on the lattice was also determined as described above.

At the initial stage of commissioning works, raw coal of 50–150 mm class was used at the plant with a wide size range: from 0 to 150 mm (Table 2), which made it difficult to maintain a uniform stable mode of volatile substances combustion within the whole area of chain-grate stoker.

At the next stage of the experimental study on the recommendation of the JSC «Eastern Research Institute of Coal Chemistry» (Kuznetsk), we used coal of the class of 25-50 mm (Table 2). When using this class of coal, uniform heating and combustion of coal within the area of chain-grate stoker is achieved, this contributes to more efficient temperature control. At this stage, several modes on the speed of the lattice and the height of the coal layer were worked out. Under these conditions, the temperatures in the coking zone reached stable values and ranged from 700 to 1100°C. By the end of the furnace space with a temperature of about 960-1050°C, the quality of the product stabilized, the yield of volatile substances ranged from 10 to 24%, an average of 15.5%. Summary results are shown in Table 3.

Table 3. Summary of the quality of the carbonaceous reducing agent obtained from the used coals

Stage	Class of coal,	Particle size distribution, %					d_{av}, mm	Technical analysis, %			
	mm	> 40	40-20	20-10	10-5	5-0		W^r	A^d	V^{daf}	C_{fix}
I	50-150	16.8	20.2	19.1	30.6	13.3	19.9	20.3	16.4	25.1	62.6
	max.	29.8	38.1	31.4	49.1	19.3		43.4	38.9	37.1	
	min.	5.1	9.2	9.3	15.6	6.3		4.5	2.7	5.7	
II	25-50	4.0	9.2	32.1	49.0	5.7	13.4	32.9	14.2	15.5	72.5
	max.	11.6	25.3	41.3	64.1	8.8		40.6	22.8	20.9	
	min.	1.6	4.2	23.0	25.1	2.7		24.1	8.5	8.6	

Table 4 shows that by using the class of 25-50 mm coal and examined coking conditions, a better reducing agent quality in comparison with experiments on charcoal classes of 50-150 mm was obtained, namely, the yield of fines decreases from 5–0 mm from 13.3 to 5.7%, respectively, the yield of the target reducing agent increases from 20–5 mm from 49.7 to 81.1%, the yield of volatile substances decreases from 25.1% to 15.5%, the content of fixed carbon C_{fix} increases from 62.6 to 72.5%. Figure 5 shows the resulting reducing agent with a highly extended surface.

Conducting, an experimental study generally confirmed previously obtained by calculation values of the main process parameters (Table 1). The best quality reductant should be considered as a mode with parameters of the coking process at a speed w=7.5 ÷ 9 m/h, a height of coal layer h = 200 mm, and temperature in active combustion zones of about 1000°C (Table 4). With such parameters, it is possible to obtain a reducing agent with a yield of volatile substances of 14 ÷ 18% (Table 4) and its output at the level of 55 ÷ 58%.

a) b)

Figure 5. The reducing agent of Shubarkol coal; a - after thermo-oxidative coking; b - from the top of the ferroalloy furnace

Table 5. Chain grate coking mode

Experiment №	*w*. m/h	*h*. mm	Temperature by zones (average). °C				Air flow by zones (gate position). %				Heat removal rates. MW	Metal temperature (on chain grate sides), °C	
			1	2	3	4	gen.	1	2	3		left	right
7	9	200	617	757	1020	958	28	22	22	21	11.7	49	160

During absorbing the technology of thermo-oxidative coking under the practical conditions of shop accounting, the yield of reducing agent increased gradually from 19 to 45%. In real production conditions, the maximum achieved yield of reducing agent was 52.5%. Calculations show that the yield of the gross reducing agent with an average level of volatile matter yield of 17% (at a loss in the yarn of about 10%) is 56.6%.

Thus, when operating in the described coking mode (Table 5), taking into account the accepted average idle time of 12%, the productivity of one unit of reducing agent can be achieved at 54 tons per day or 17.4 thousand tons per year. Experiments revealed that the installation could be operated for a short time at a grade speed of 12 m/h with a capacity of 72 tons of product per day.

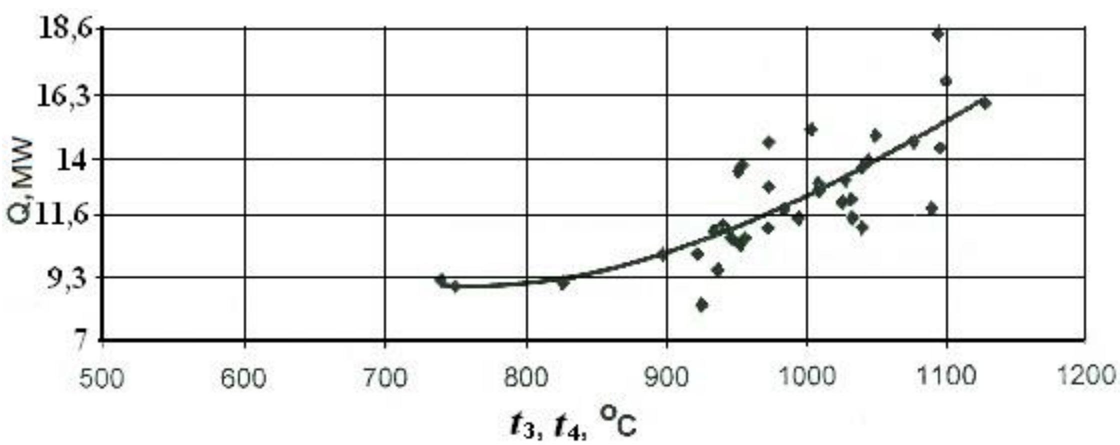

Figure 6. The dependence of the generated heat amount on the temperature in zones 3 and 4

The tests proved the possibility of combining processes of thermal power generation with the production of the carbonaceous reductant in the described installations with direct drive chain-grate stoker in the listed modes of coking (Figure 6).

Maximum heat removal (14-17.5 MW) is achieved at temperatures in the active zones of 1100°C or more. However, on the basis of the conditions for obtaining coke, the mode with temperature in the latter zones at 1000°C should be considered rational. In this mode, the plant is capable of carrying a heat load in the form of hot boiler water at a level of 11.5-13 MW with a nominal value of the boiler installation of 23 MW (20 Gcal/h)

6. Conclusions

The possibility of using standard boilers with a grate-fired furnace on a chain grate as an energy technology unit for the joint production of thermal energy and special-purpose coke is substantiated.

When comparing the model temperature field with the experimental ones, we note:

- the nature of the simulated curves, in general, corresponds to the actual processes occurring during thermal-oxidative coking;
- if we divide the layer of coal inside the furnace into four equal parts along the length of the grate, in the first two zones, the experimental values fall within the range of calculated temperatures. In the third zone and the beginning of the fourth, there is some discrepancy between them. In fact, the temperature increase occurs more intensively than in the modeled process, which can be explained by the uneven burning of the lower layer - the carbon loss along the length of the grate. The maximum deviation is 6.6% in the plane of 4.875 m or 0.5445 hours. By the end of the fourth zone, the compared curves again become commensurate with the values.

Thus, the developed model is adequate to the available experimental data and can be used to predict various production situations in the process of thermal-oxidative coal feed coking.

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To whom correspondence should be addressed: Dr. Mikhail Zhumagulov, Transport and Power Energy Faculty, L. N. Gumilyov Eurasian National University, Nur-Sultan, Aytmatov str., 31b – 117, Republic of Kazakhstan