Development and Software Implementation of the Hot Blast Stove Computer Model

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Abstract. Based on the evaluation of the existing methods of regenerative heat exchangers modeling, and, in particular, hot blast stoves of blast furnaces, an algorithm for calculating of heat exchange in full cycle "on-gas" and "on-blast" was proposed and implemented as a computer application. The computer model includes adjustment coefficients, the values of which were determined based on the database of technological parameters of an actual hot blast stove block. The modeling results correspond to the actual mill data, it showing the adequacy of the developed model. The computer application will be implemented in the automatic control systems of a hot blast stoves block.

Keywords: model, computer application, regenerator, hot blast stove, HBS, checkerwork, heat exchange, flow-chart

1 Introduction

Several regenerative heat exchangers (hot blast stoves, hereinafter referred to as HBSs) merged in a block are used for the preparation of blast air required for the production of cast iron in a blast furnace. The design of HBSs does not allow to control a number of parameters of their operation, in particular, the temperature of the checkerwork along its height.

There are various approaches to the simulation of the regenerative heat exchange, which happens in HBS.

It is necessary to use computer models to estimate the condition of HBSs, to optimize the operation of the block and stabilize the blast air temperature.

The objective of the research is to develop an HBS computer simulation model, capable of solving technological problems and being used in automation systems.

To achieve the objective it is necessary to solve the following problems:

1. To study the current state of the simulation of the regenerative heat exchange.
2. To develop a mathematical model of the HBS operation in the "on-gas" and "on-blast" periods.
3. To develop an algorithm for the implementation of the above model.
4. To implement the developed algorithm in the form of a computer application.
5. To evaluate the simulation results by comparing them with the actual mill data.

2 Formal problem statement

The HBS checkerwork is a cylinder lined with the chequer bricks in such a way that vertical channels are formed along its height. The checkerwork accumulates the heat during the operation of HBS in the on-blast period. Hot flue gases produced by combustion of blast furnace gas (hereinafter referred as BFG) in the combustion chamber at temperature $t_{\text{g}} = f(\tau)$ enter the checkerwork from the top and descend down through the channels, yielding the heat to the checkerwork, and then enter the flue gas collector. The duration of the checkerwork heating depends on the initial temperature distribution in the checkerwork $t_{\text{s}} = f(y)$, the material of the checkerwork and the parameters of the exchange gas (Fig. 1, a). The on-gas period continues until the flue gases temperature at the outlet of the checkerwork reaches the maximum possible temperature, usually $300 \div 400$ °C, which is due to HBS design features.

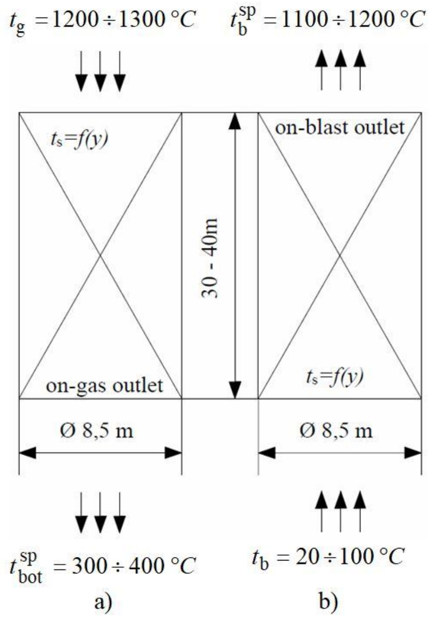

Fig. 1. Physical model of heating (a) and cooling (b) of the checkerwork

The accumulated checkerwork heat Q_{ch}^{a} is used to heat the blast air. The pressurized blast air at temperature t_{b} enters the checkerwork from the bottom and passing its channels heats up to the required temperature (Fig. 1, b). The on-blast period lasts until the temperature of the blast air at the checkerwork outlet reaches a set-point temperature t_{b}^{sp}.

Up to now the methods for the mathematical description of gas dynamics and convective heat exchange have been developed in sufficient detail [1 - 3]. While investigating this problem the authors of the research paid attention to description of these processes in a granular bed. When describing the granular bed the actual structure is replaced with an ideal structure, which is a set of cylindrical vertical channels parallel to each other [4], similar to the checkerwork consisting of shaped elements. Therefore the mathematical methods used for the granular beds can also be fully used for the checkerwork [2, 4].

Now, let us consider the heat exchange in a fixed granular bed. The gas passes in time $d\tau$ at the velocity of open flow u_o through the element of the layer dy at a distance y from the delivery point of the gas to the layer with the porosity ε and a cross section of 1 m^2. In this case 1 m^3 of the layer accounts for layer porosity ε m^3 of gas, and the percentage of particles - $(1-\varepsilon)m^3$ (Fig. 2).

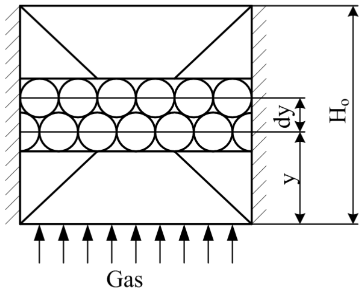

Fig. 2. Fixed granular bed

To describe the heat exchange by simple dependencies, we take a number of assumptions:

- the layer of particles is homogeneous in its fractional composition, and the thermophysical parameters of the bed and the gas are constant and acquire their average values within the range of operational temperatures, besides, the heat transfer in the gas and in the bed from particle to particle due to thermal conductivity is nonexistent;
- the heat flow from the gas to the bed at any point is determined by Newton's law, and the heat exchange coefficient from the gas to the bed is the same along the entire height and section of the bed;
- gas flow rate in time is the same and equally distributed over the cross section of the bed.

In this case the change in gas enthalpy in the elementary layer is determined as follows:

$$d^2Q = c_g \rho_g \varepsilon \frac{dt_g}{d\tau} dy d\tau = c_g \rho_g \left(\varepsilon \frac{\partial t_g}{\partial \tau} - u_o \frac{\partial t_g}{\partial y} \right) dy d\tau , \qquad (1)$$

where c_g – heat capacity, J/kgK ; ρ_g – gas density, kg/m^3 .

The amount of heat that the gas gives to the bed when goes through it

$$d^2Q = \alpha_V \left(t_{\mathrm{g}} - t_{\mathrm{s}}\right) dy d\tau \, , \tag{2}$$

where α_V – volumetric heat transfer coefficient, $\mathrm{W/m^3K}$.

Considering the heat exchange from the bed material side and bearing in mind that the material will be changed in the elementary layer in time only, given that the material is fixed, we can write:

$$\alpha_V \left(t_{\mathrm{g}} - t_{\mathrm{s}}\right) = C_{\mathrm{s}} \rho_{\mathrm{s}} \frac{\partial t_{\mathrm{s}}}{\partial \tau} \, , \tag{3}$$

where C_{s} – solid specific heat capacity, $\mathrm{J/kgK}$; ρ_{s} – solid density, $\mathrm{kg/m^3}$.

Let us consider and evaluate different approaches to the description of the heat exchange in regenerative heat exchangers.

3 Literature review

The study of heat exchange in the checkerwork of a regenerative heat exchanger (hereinafter referred to as a regenerator) developed in parallel with the theory of heat exchange in a fixed bed.

Customary mathematical modeling of heat exchange in the bed is based on several approaches: a model of an equivalent recuperator; temperatures of the gases and the material are essentially the same; temperatures of the gases and the bed material are essentially different.

The first approach at the present stage is not relevant, since it does not reflect the principles of regenerative heat exchange. The second approach is not widespread.

The third approach assumes that the heat exchange in the regenerator checkerwork is characterized by the fact that the temperatures of the gases and the bed material differ significantly. Based on the principle, various authors developed a direction in calculating temperature fields in the bed and checkerworks, based on the assumption that the longitudinal thermal conductivity in the bed was non-existent. In this case the equation system describing the heat exchange consists of separate heat exchange equations for the gas and the bed material. These equations were analyzed analytically by T. Schumann [5], H. Hausen [1, 6], A. Willmott [7, 8], etc.

T. Schumann [4] considered the problem of the heat exchange between a liquid and a porous cylinder, while the cylinder material temperature at the start of the heat exchange was uniform (equal along the layer), the gas was supplied at constant temperature and flow. Moreover, the author made a number of other assumptions. The problem does not fully describe the regenerative heat exchange in the regenerator checkerwork. In [9], the solution of T. Schumann's problem was obtained by applying numerical methods, it was used as a model to study the effect of the exchange gas pressure on the intensification of the heating of the regenerator checkerwork.

H. Hausen [6] developed a method for the approximate calculation of temperature fields in a checkerwork at the end of heating (cooling) for a set-point initial temperature distribution, based on the linearity of differential equations. The initial temperature field is approximated at that with a stepped line, in such a way, that the temperature in each individual section is assumed to be constant.

The method proposed by A. Willmott [7, 8] happens to be general and can be used to solve most non-linear problems of calculating the heat exchange in regenerators with a digital computer. The author complicated his model by introducing a variable velocity of the gas flow and used the dependence of the thermo-physical parameters of the gas and the checkerwork material upon temperature.

P. Razelos [10] applied the heat exchange coefficient, which includes convective and radiant components. The developed computer program for calculating heat exchange in the checkerwork included in the form of tables the thermo-physical properties of the checkerwork material and gases, that depend on the temperature.

The authors K. Muske and F. Minet [11 - 13] divided the HBS checkerwork into several zones corresponding to different checkerwork materials, and the dependences of the heat capacities and viscosities for each of the gas components and the material thermal conductivity were used as approximating polynomials of table values. The disadvantages of the approach include the fact that the gas flow was considered uniform and the thermal conductivity in the radial direction was not taken into account. The obtained models identified on the basis of mill data and were used to optimize the operation of the HBSs block. The work [13] describes a model that uses for calculations the values of technological parameters measured with an interval of two minutes.

The author of [14] proposed a three-dimensional mathematical model that can simulate various complex phenomena such as turbulent mixing of fuel and air, combustion, convection floatation, thermal radiation, heat exchange between the gas and the heat-retaining brick.

To study the operation of new types of dome burners, the authors of [15] implemented a 3D mathematical model of HBS considering the basic regularities of heat exchange using the ANSYS Fluent program.

The authors of [16, 17] developed a finite-difference mathematical model of HBS based on an approximate thermal balance with regard to the gas flow, convective and radiant heat exchange. The model allows to take into account the design features and the technical condition of each of HBS.

The article by E. Kobysh [18, 19] presents the solution of a system of equations describing regenerative heat exchange considering the heating of the checkerwork throughout the thickness of a brick, allowing to solve problems of external and internal heat exchange.

For investigation of the heat exchange during the on-gas period from the balls, a mathematical simulation model was proposed [20] based on the finite difference method for iteratively solving the heat exchange problem in the checkerwork. In this case, only the on-gas period is considered.

Thus, at present, a sufficient number of models of the heat exchange process in HBSs has been created and implemented. In order to improve the accuracy of modeling and taking into account the basic regularities, the authors of this research decided to develop a simulation model based on an analytical solution of the heat exchange problem in a fixed bed.

4 Formalization and mathematical representation of the model

To analyze the operation of the actual HBS during the on-gas – on-blast cycle, it is necessary to solve the general problem under the following conditions:

- variable gas temperature at the inlet to the checkerwork;
- uneven initial temperature distribution of the material of the checkerwork along its height.

The general problem of the heat exchange in the checkerwork [1] in an analytical form possesses the following view:

$$\frac{\partial t_{\mathrm{s}}}{\partial Z} = t_{\mathrm{g}} - t_{\mathrm{s}}, \quad -\frac{\partial t_{\mathrm{g}}}{\partial \mathrm{Y}} = t_{\mathrm{g}} - t_{\mathrm{s}}, \tag{4}$$

at border-line conditions

$$t_{\mathrm{g}}(\mathrm{Y}=0) = \varphi(Z), \quad t_{\mathrm{s}}(\mathrm{Z}=0) = f(Y), \tag{5}$$

where Z – dimensionless time; Y – dimensionless checkerwork height.

The solution to problem (4) is presented as a combination of two solutions with different border-line conditions:

1. Uneven temperature distribution of the checkerwork along its height at a constant temperature of the exchange gas at the checkerwork inlet:

$$t_{\mathrm{g}}(\mathrm{Y}=0) = 1, \quad t_{\mathrm{s}}(\mathrm{Z}=0) = f(Y). \tag{6}$$

2. Uniform temperature distribution of the checkerwork along its height at a variable in time temperature of the exchange gas at the checkerwork inlet:

$$t_{\mathrm{g}}(\mathrm{Y}=0) = \varphi(Z), \quad t_{\mathrm{s}}(\mathrm{Z}=0) = 0. \tag{7}$$

The solution of the problem under conditions (6) has the following form [3]:

$$t_{\mathrm{g}} = -\int_{0}^{Y_{\mathrm{H}}} f(Y) \frac{\partial \theta (Y_{\mathrm{H}} - Y)}{\partial (Y_{\mathrm{H}} - Y)} dY, \quad t_{\mathrm{s}} = f(Y_{\mathrm{H}}) \cdot e^{-Z} - \int_{0}^{Y_{\mathrm{H}}} f(Y) \frac{\partial \vartheta (Y_{\mathrm{H}} - Y)}{\partial (Y_{\mathrm{H}} - Y)} dY, \tag{8}$$

where θ – relative dimensionless gas temperature; ϑ – relative dimensionless solid temperature; Y_{H} – dimensionless checkerwork height at $H_{\mathrm{o}} = 30\ \mathrm{m}$;

Dividing the height of the checkerwork Y_{H} into n sections, assuming the checkerwork temperature on the section is equal to the average of its height, we replace the analytical formulas (8) with finite amounts, and get the following expressions:

$$t_{\text{g}} = \sum_{i=1}^{n} \left(f_i(Y_{\text{H}}) \cdot \left[\theta(Y_{\text{H}} - Y_i, Z) - \theta(Y_{\text{H}} - Y_{i-1}, Z) \right] \right), \tag{9}$$

$$t_{\text{S}} = f(Y_{\text{H}}) \cdot e^{-Z} + \sum_{i=1}^{n} \left(f_i(Y_{\text{H}}) \cdot \left[\vartheta(Y_{\text{H}} - Y_i, Z) - \vartheta(Y_{\text{H}H} - Y_{i-1}, Z) \right] \right). \tag{10}$$

Taking the initial change in the material temperature of the checkerwork along its height as linear

$$f_i = a_i + b_i \cdot y, \tag{11}$$

and inserting (11) into equations (9) and (10), we obtain the following expressions for determining the temperatures of the gas and the material in the checkerwork at any time [21]:

$$t_{\text{g}} = \sum_{i=1}^{n} \left(\left[a_i + b_i \cdot Y_{\text{H}} \right] \cdot \left[\theta(Y_{\text{H}} - Y_i, Z) - \theta(Y_{\text{H}} - Y_{i-1}, Z) \right] \right), \tag{12}$$

$$t_{\text{S}} = f(Y_{\text{H}}) \cdot e^{-Z} + \sum_{i=1}^{n} \left(\left[a_i + b_i \cdot Y_{\text{H}} \right] \cdot \left[\vartheta(Y_{\text{H}} - Y_i, Z) - \vartheta(Y_{\text{H}} - Y_{i-1}, Z) \right] \right), \tag{13}$$

where a_i, b_i – linear equation coefficients; n – the number of iterations affecting the accuracy.

Similar to the above, the solution to the problem with the border-line conditions (7) has the form [3]

$$t_{\text{g}} = \varphi(Z_\Sigma) e^{-Y} - \int_0^{Z_\Sigma} \varphi(Z) \frac{\partial \theta(Z_\Sigma - Z)}{\partial (Z_\Sigma - Z)} dZ, \quad t_{\text{s}} = -\int_0^{Z_\Sigma} \varphi(Z) \frac{\partial \vartheta(Z_\Sigma - Z)}{\partial (Z_\Sigma - Z)} dZ, \tag{14}$$

determining the temperature of the exchange gas for the consecutive time periods

$$\varphi_j = \alpha_j + \beta_j Z, \tag{15}$$

and inserting expression (15) into (14) and making mathematical simplifications, we obtain the solution in numerical form

$$t_{\text{g}} = \varphi(Z_\Sigma) e^{-Y} + \sum_{j=1}^{m} \left(\varphi_j(Y) \left[\theta(Y, Z_\Sigma - Z_j) - \theta(Y, Z_\Sigma - Z_{j-1}) \right] \right), \tag{16}$$

$$t_{\text{S}} = \sum_{j=1}^{m} \left(\varphi_j(Z_\Sigma) \left[\vartheta(Y, Z_\Sigma - Z_j) - \vartheta(Y, Z_\Sigma - Z_{j-1}) \right] \right), \tag{17}$$

where Z_Σ – dimensionless time at which the maximum temperature of the exchange gas is reached; α_j, β_j – linear equation coefficients; j – time section number ($j \in [1, m]$); m – the number of time partitions.

By combining expressions (13), (14) and (18), (19), the authors of this research obtained a solution to the general problem of the heat exchange in the following form:

$$\begin{aligned} t_{\text{g}} &= \sum_{i=1}^{n}\left(f_i\left(Y_{\text{H}}\right)\left[\theta\left(Y_{\text{H}}-Y_i,Z\right)-\theta\left(Y_{\text{H}}-Y_{i-1},Z\right)\right]\right)+ \\ &+\varphi\left(Z_{\Sigma}\right)e^{-Y}+\sum_{j=1}^{m}\left(\varphi_j(Y)\left[\theta\left(Y,Z_{\Sigma}-Z_j\right)-\theta\left(Y,Z_{\Sigma}-Z_{j-1}\right)\right]\right) \end{aligned} \tag{18}$$

$$\begin{aligned} t_{\text{s}} &= f\left(Y_H\right)e^{-Z}+\sum_{i=1}^{n}\left(f_i\left(Y_{\text{H}}\right)\left[\vartheta\left(Y_{\text{H}}-Y_i,Z\right)-\vartheta\left(Y_{\text{H}}-Y_{i-1},Z\right)\right]\right)+ \\ &+\sum_{j=1}^{m}\left(\varphi_j\left(Z_{\Sigma}\right)\left[\vartheta\left(Y,Z_{\Sigma}-Z_j\right)-\vartheta\left(Y,Z_{\Sigma}-Z_{j-1}\right)\right]\right) \end{aligned} \tag{19}$$

In works [3], nomograms were used to determine the relative temperatures at the dimensionless layer height and time, which in its turn reduces the accuracy of calculations and makes it impossible to use a PC. At the same time, the author of [5] proposed the following analytical expressions for determining relative temperatures:

$$\vartheta = e^{-Y}\int_0^Z e^{-\delta}\sum_{k=0}^{\infty}\frac{\left(2\sqrt{Y\delta}/2\right)^{2k}}{(k!)^2}d\delta\,,\ \theta = 1-e^{-Z}\int_0^Y e^{-\delta}\sum_{k=0}^{\infty}\frac{\left(2\sqrt{Z\delta}/2\right)^{2k}}{(k!)^2}d\delta\,. \tag{20}$$

After a number of simplifications and integration, solutions (22) and (23) will have the following form [9]:

$$\vartheta = e^{-Y}\left(\sum_{i=0}^{n}\left(\frac{Y^i}{i!}\left(1-e^{-Z}\sum_{k=0}^{i}\frac{Z^k}{k!}\right)\right)\right),\ \theta = 1-e^{-Z}\left(\sum_{i=0}^{n}\left(\frac{Z^i}{i!}\left(1-e^{-Y}\sum_{k=0}^{i}\frac{Y^k}{k!}\right)\right)\right). \tag{21}$$

The solutions obtained by the authors of this research (18) and (19) and expressions (21) allow further calculations to be made with application of a PC, it improving the accuracy of the calculations.

5 Development of the algorithm for program implementation of the model

Fig. 3 represents a general flow-chart of the program. Let us consider the algorithm in further detail.

In block 1 the input and values assignment are carried out: of the initial temperature distribution of the checkerwork material along its height; of the exchange gas temperature at the checkerwork inlet in the on-gas period; the cold blast air temperature at the checkerwork inlet in the on-blast period; time step (by default - 100 s); number of partitions throughout the checkerwork height; checkerwork height, diameter, channel diameter and porosity; correction coefficients that consider the checker-

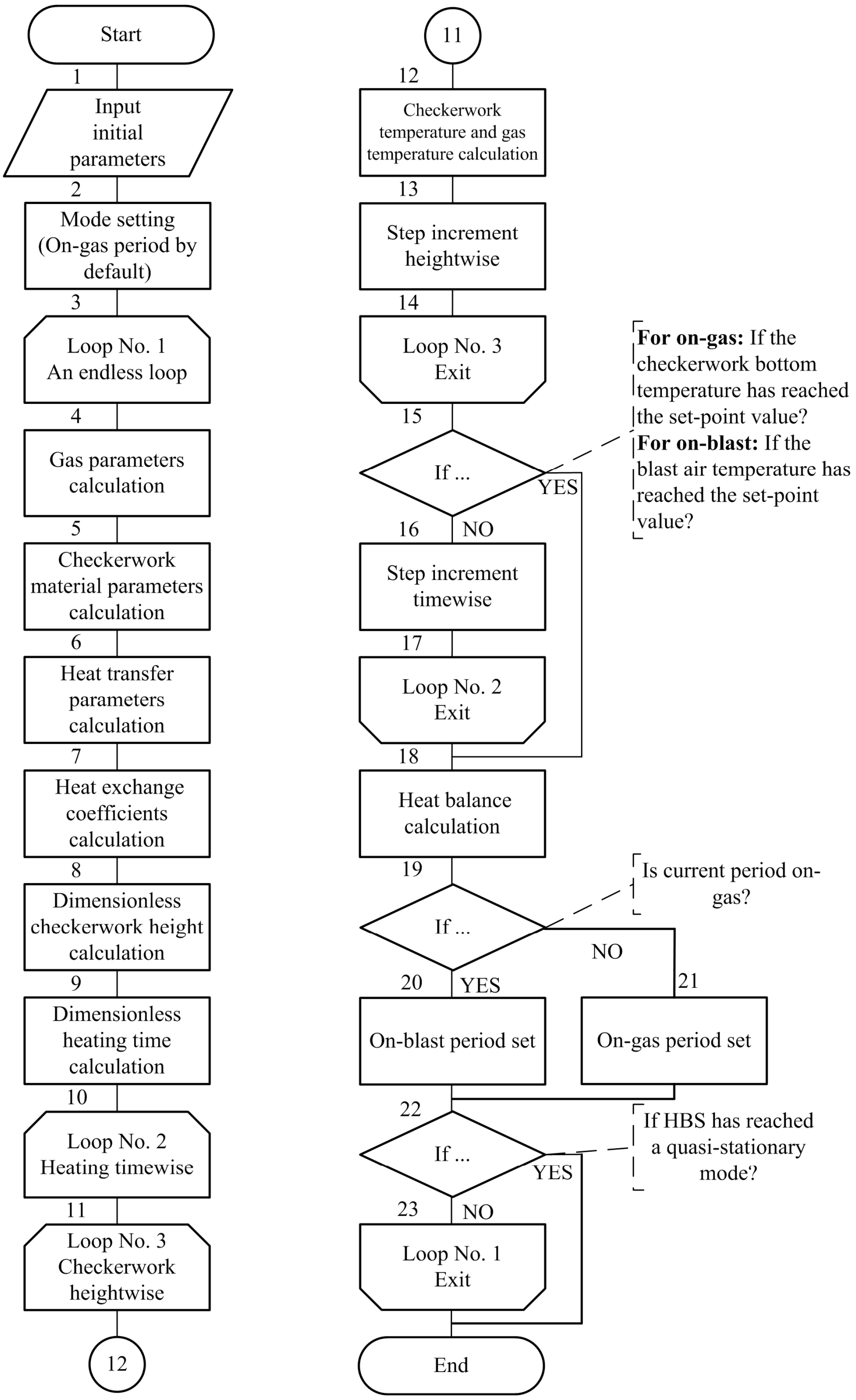

Fig. 3. General flow-chart of the algorithm of the program

work state; accuracy of calculations (2.5 – 5 ºC); flow rate, pressure and chemical composition of the exchange gas; flow rate, pressure and chemical composition of the blast air; set-point temperature value of the checkerwork bottom while heating of the checkerwork (300 – 400 ºC), at which the on-gas period ends; set-point temperature value of the blast air at the checkerwork outlet during the heating period of the blast air (1100 – 1250 ºC), at which the on-blast period ends.

In block 2 the mode of operation of HBS stove is set (on-gas or on-blast). The on-gas is automatically set when the program starts.

In block 3 an endless loop No. 1 starts, it ends when the HBS operation reaches a quasi-stationary mode – similar on-gas and on-blast periods are repeated three times.

In block 4 the following parameters of the exchange gas or blast air are calculated depending on the average temperature and overpressure: average temperature during on-gas or on-blast; density; mass heat capacity; volumetric heat capacity; kinematic viscosity; dynamic viscosity; thermal conductivity; velocity actual and reduced to normal conditions.

In block 5 the following parameters of material of the checkerwork are calculated depending on the average temperature: average temperature during the on-gas or on-blast; heat capacity; thermal conductivity.

In block 6 the parameters of heat exchange are calculated: the criteria of Reynolds, Peclet, Prandtl, Nusselt, Biot and thermal conductivity coefficient.

In block 7 heat exchange coefficients relative to volume and surface area are calculated. Correction for thermal massiveness is introduced [22, 23].

In block 8 the dimensionless height of the checkerwork is calculated.

In block 9 the dimensionless heating time of the checkerwork is calculated.

At the region of the program (blocks Nos. 10–17), a loop No. 2 is performed with iterations on the checkerwork heating timewise. The loop exit is performed on reaching the set-point accuracy of the set-point checkerwork bottom temperature value for the on-gas period or the set-point blast air temperature value at the checkerwork outlet for the on-blast period.

At the region of the program (blocks Nos. 11–14) a loop No. 3 is performed with iterations on the checkerwork heightwise at the current heating time. The loop exit is performed on reaching the end of the checkerwork.

In block 12 the calculation of the temperature of the checkerwork and of gas at the current time of heating according to (18) and (19) are performed. In block 13 the transition to the next layer of the checkerwork along its height is performed. In block 14 the exit from the loop 3 is performed.

Block 15 carries out a check: For on-gas period: if the bottom of the checkerwork temperature has reached the set-point value? For the on-blast period: if the blast air temperature has reached the set-point value? If it did, then an exit from the loop No. 3 and the transition to block 18 is performed, if NOT - to block 16.

In block 16 the time step is incremented.

In block 17 the exit from the loop No. 3 is performed.

In block 18 the calculation of the heat balance of the heating cycle is performed.

Block 19 carries out a check: current period – on-gas? If YES – transition to block 20, if NOT - transition to block 21.

In block 20 the HBS operation mode – on-blast period is set.

In block 21 the HBS operation mode – on-gas period is set.

Block 22 carries out a check: if HBS has reached a quasi-stationary mode? If YES – transition to the end of the program, if NOT - transition to block 3.

Based on the dependencies (21) and (22) generated by the authors, an application was developed using MS Visual Studio, the object-oriented programming environment, the application allows to analyze the operation of HBS in the on-gas – on-blast cycle. The program runtime varies from 0.2 to 120 s depending on the number of partitions throughout the checkerwork height and the configuration of PC. Part of the source data is entered using dialog boxes. The initial data on the initial temperature distribution throughout the checkerwork height, the intermediate and final results of the application operation are presented as Excel files with an option to view input and output data in the form of values and graphs.

6 The experiment and results

To determine the model operation adequacy, the parameters of HBSs of the existing block (hereinafter referred to as HBS1, HBS2, HBS3 and HBS4) were taken: checkerwork dimensions, checkerwork block parameters, parameters of BFG and air taken for combustion, as well as graphs of temperature changes of the checkerwork bottom and the dome of both periods. The study block operated in a sequential mode, and this mode was maintained by the sequential operation of HBS1 and HBS4, which are in a good condition, and by the parallel operation of HBS3 and the worn-out HBS2.

The on-blast period was simulated at the completely closed mixing valve – the hot blast air temperature was not stabilized before being supplied into the blast furnace. The exchange gas parameters (density, heat capacity, thermal conductivity, viscosity) in the model are presented as functions of pressure and temperature in the form of polynomials obtained from tabular data of reference books [24, 25]. The program implementing the model was completed when HBS was put into quasi-stationary mode of operation.

The authors of this research processed the technological parameters databases for the HBS block for the 4 months period. Periods that were significantly less or longer than the average duration of the periods, as well as periods for which the values of the technological parameters do not correspond to the working range, are excluded from the processing.

In order to further study the HBS operating periods, the simulation model was adjusted with application of tuning coefficients, which allow considering the current state of HBSs, primarily – of the regenerative checkerwork.

Fig. 4 shows the graphs of the variation of the dome temperatures (at the left) and the grid space (at the right) for each HBS of block, operating in the on-blast (a black line) and on-gas (a gray line) periods, which were obtained using simulation results (a dashed line) and production data (a continuous line).

In Fig. 4 lines, corresponding to the operating HBS, are built on the basis of data processing for more than 350 on-blast – on-gas cycles. The calculated maximum con-

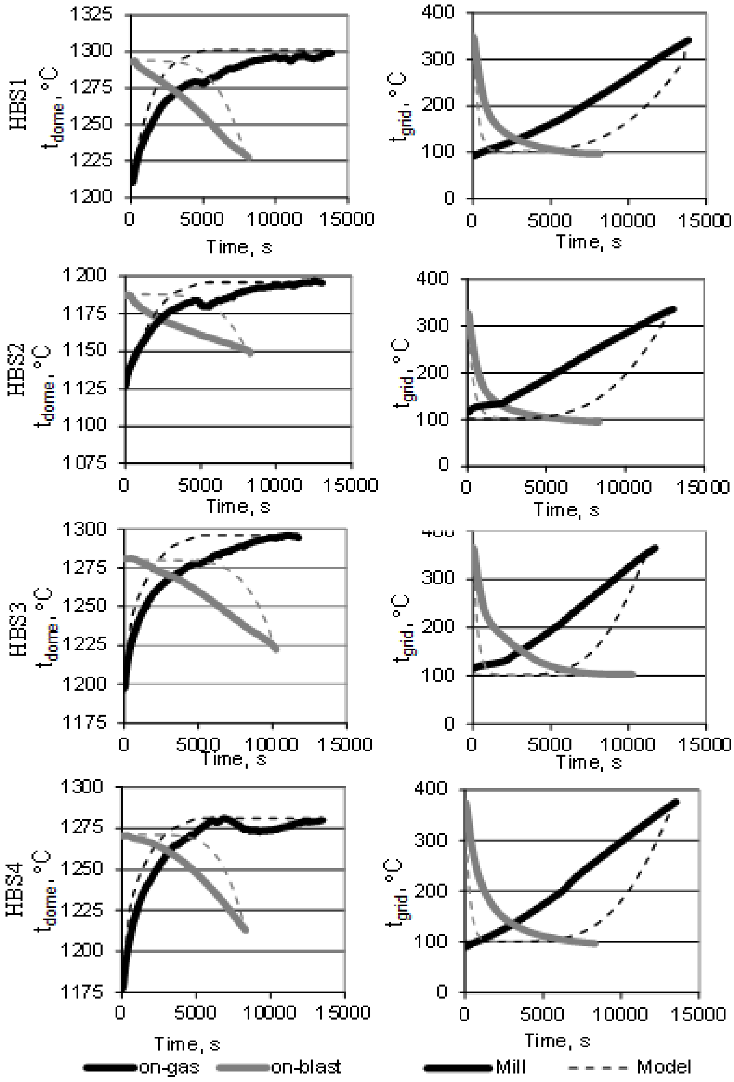

Fig. 4. Changes in the temperature of the dome t_{dome} and the grid device of HBS t_{grid} during the on-gas and on-blast periods

fidence interval for each value is ± 5 ºC. According to the mill technological instruction, the maximum measurement error of the technical means complex for measuring the dome temperature is 12 ºC, and the grid device temperature is 4 ºC. The adequacy of the model is confirmed by the calculation of the Fisher criterion for each of the temperatures: the experimental values of the Fisher criterion are less than the tabulated ones.

The simulation results correspond to the processed values from the automation system database. It should be noted that of the flue gases temperature is measured in the grid device space and, likewise it does not correspond to the gas temperatures in the checkerwork bottom layer, calculated by the model.

To assess the correct model functioning, the heat balance (Table 1) was simultaneously calculated for the on-blast and on-gas periods in accordance with the procedure [26]. The data (Table 1) indicate that certain balance sheet items represent the numbers of the same order and differ in the range from 1 to 8%.

Table 1. Heat balance of an operating HBS and simulation results

Parameter, TJ	Model results				Mill data				Deviation, %			
	HBS1	HBS2	HBS3	HBS4	HBS1	HBS2	HBS3	HBS4	HBS1	HBS2	HBS3	HBS4
On-gas period												
Initial checkerwork heat $Q^{\mathrm{i}}_{\mathrm{ch}}$	0.494	0.217	0.307	0.392	0.513	0.237	0.332	0.418	4	8	8	6
Checkerwork heat after heating	1.109	0.453	0.757	1.028	1.128	0.488	0.806	1.105	2	7	6	7
Accumulated heat $Q^{\mathrm{a}}_{\mathrm{ch}}$	0.614	0.235	0.450	0.636	0.601	0.237	0.443	0.595	2	1	2	7
Flue gas heat $Q^{\mathrm{f}}_{\mathrm{g}}$	0.078	0.034	0.061	0.086	0.084	0.037	0.064	0.093	7	6	4	8
Exchange gas heat $Q^{\mathrm{e}}_{\mathrm{g}}$	0.698	0.270	0.517	0.728	0.718	0.282	0.517	0.721	3	4	1	1
On-gas period heat balance												
$\left(Q^{\mathrm{a}}_{\mathrm{ch}} + Q^{\mathrm{f}}_{\mathrm{g}}\right)/Q^{\mathrm{e}}_{\mathrm{g}}$	0.99	1.00	0.99	0.99	0.95	0.97	0.98	0.95	-			
On-blast period												
Blast air heat $Q^{\mathrm{b}}_{\mathrm{g}}$	0.63	0.24	0.46	0.65	0.61	0.23	0.45	0.63	4	4	1	3
“On-gas – On-blast” cycle heat balance												
$Q^{\mathrm{a}}_{\mathrm{ch}}/Q^{\mathrm{b}}_{\mathrm{g}}$	1.02	1.02	1.01	1.02	1.01	0.96	1.02	1.06	-			

Furthermore the adequacy of the model was also confirmed: in work [27] during an on-site research of the regenerative heat exchanger operating at overpressure; by using the computer application described in work [19]. The results of the simulation obtained with the method of the authors of the research and with the method described in the article [19] are almost identical (the error is less than 2%).

7 Conclusion

Based on the review of the existing models describing the heat exchange in HBS, using the dependencies (18, 19) obtained by the authors, a computer model of HBS heat operation during different operating modes of HBS was proposed and implemented as a software application.

The adequacy of the simulation results was confirmed by the actual mill data and by the results of the model implemented on the basis of the different approach.

The model will be applied with the objective of increasing the blast air temperature: to optimize the implementation sheet of the HBS block mode; to study new types of refractories for the production of checkerworks; to assess the possibility of using the high-calorific fuel gas; to study new types of checkerworks while designing HBSs.

In automation systems, the model will be applied as an informational one, besides: it can be used to calculate the set-point values of the fuel-air parameters, dome temperature and to output these values in the control loops; to control the HBS block on the basis of estimation of the duration of the on-blast and on-gas periods.

References

1. Hausen, H.: Wärmeübertragung im Gegenstrom, Gleichstrom und Kreuzstrom. 2nd ed. Springer-Verlag, Berlin (1976)
2. Gres, L.P.: High-efficiency heating of the furnace blast [Высокоэффективный нагрев доменного дутья]. Porogi, Dnepropetrovsk (2008)
3. Kitayev, B. I., Timofeyev, V. N., et al.: Heat and mass transfer in a dense layer [Тепло- и массообмен в плотном слое]. Metallurgiya, Moscow (1970)
4. Tarasov V.P.: Gas dynamics of blast furnace process [Газодинамика доменного процесса]. Metallurgiya, Moscow (1990)
5. Schumann, T.E.: Heat transfer: a liquid flowing through a porous prism. Journal of the Franklin Institute. 208 (3): pp. 405-416 (1929)
6. Hausen, H., Binder, J.A.: Vereinfachte Berechnung der Wärmeübertragung durch Strahlung von einem gas an eine wand. International Journal of Heat and Mass Transfer. 5 (3–4): pp. 317–327 (1962)
7. Willmott, A.J.: Simulation of a thermal regenerator under conditions of variable mass flow. International Journal of Heat and Mass Transfer. 11 (7): pp. 1105-1116 (1968) doi:10.1016/0017-9310(68)90028-8
8. Willmott, A.J.: The regenerative heat exchanger computer representation. International Journal of Heat and Mass Transfer. 12 (9): pp. 997-1014 (1969) doi:10.1016/0017-9310(69)90111-2
9. Koifman, A.A., Simkin, A.I., Tomash, A.A.: Heavy pressure gases - brick checkerwork heat exchange intensification possibility [Возможность интенсификации процессов теплообмена между кирпичной насадкой и газами под давлением]. Izvestiya VUZ. Chernaya Metallurgiya, vol. 5: pp. 39-42 (2008)
10. Razelos, P., Benjamin, M.K.: Computer model of thermal regenerators with variable mass flow rates. International Journal of Heat and Mass Transfer 21 (6): pp. 735–744 (1978) doi:10.1016/0017-9310(78)90035-2
11. Muske, K.R., Howse, J.W., et al.: Hot blast stove process model and model-based controller (No. LA-UR-98-3183; CONF-980923-). Los Alamos National Lab., Computational Science Methods Group, NM (United States) (1998)
12. Muske, K.R., Howse, J.W., Hansen G.A., Cagliostro D.J.: Model-based control of a thermal regenerator. Part 1: Dynamic model. Computers & Chemical Engineering 24 (11): 2519–2531 (2000) doi:10.1016/S0098-1354(00)00614-1

13. Minet, F., Heyen, G., et al.: Dynamic data reconciliation of regenerative heat exchangers coupled to a blast furnace. Computer Aided Chemical Engineering. Elsevier, vol. 9: pp. 1053-1058 (2001) doi:10.1016/S1570-7946(01)80169-3
14. Kimura., Y., Takatani, K., Otsu, N.: Three-dimensional mathematical modeling and designing of hot stove. ISIJ International 50 (7): pp. 1040–1077 (2010) doi:10.2355/isijinternational.50.1040
15. Qi, F., Liu, Zh., Yao, Ch., et al.: Numerical Study and Structural Optimization of a Top Combustion Hot Blast Stove. Advances in Mechanical Engineering. 7(2): 10-19 (2015) doi:10.1155/2014/709675
16. Zetterholm, J., et al.: Model Development of a Blast Furnace Stove. Energy Procedia. Vol. 75: pp. 1758-1765 (2015)
17. Zetterholm, J., et al.: Dynamic modelling for the hot blast stove. Applied Energy, 185 (2): pp. 2142-2150 (2017) doi:10.1016/j.apenergy.2016.02.128
18. Kobysh, E.I., Simkin, A.I., Kravchenko, V.P.: Heating of the packing in a blast-furnace air heater with an internal combustion chamber. Steel in Translation. 44 (1): pp. 38-42 (2014) doi:10.3103/S0967091214010094
19. Simkin, A.I., Kobysh, E.I.: Control model of the heating hot blast stove regenerative chamber based on fuzzy knowledge with training set. Metallurgical and Mining Industry. 7 (6): pp. 96-101 (2015)
20. Zhang, H., Jiang, Z., Cheng, Z., Gui, W., et al.: Two-Stage control of endpoint temperature for pebble stove combustion. IEEE Access. Vol. 7: pp. 625-640 (2019) doi:10.1109/ACCESS.2018.2885581
21. Koifman, A.A., Simkin, A.I., Tomash, A.A. Modeling of heating of checkerwork of hot blast stove operating under pressure [Моделирование нагрева насадки доменного воздухонагревателя, работающего под давлением] Reporter of Priazovskyi State Technical University: Collection of scientific papers – Part 2. Vol. 19: pp. 203-206 (2009)
22. Solomentsev, S.L.: Rational types of checkerworks and hot blast stoves [Рациональные типы насадок и доменных воздухонагревателей]. Lipetsk State Technical University, Lipetsk (2001)
23. Wegman, E.F. (eds): Blast Furnace Production: Reference Edition [Доменное производство: Справочное издание в 2–х томах]. Vol. 1, Metallurgy, Moscow (1989)
24. Vargaftik, N.B., Vinogradov, Y.K., Yargin, V.S.: Handbook of physical properties of liquids and gases. Pure Substances and Mixtures. Begell House (1996)
25. Hilsenrath, J., Beckett, C. W., Benedict, W. S., et al: Tables of thermal properties of gases. Technical Report 564, National Bureau of Standards, (1955)
26. Koifman, A.A., Simkin, A.I.: Thermal balance of regenerative heat exchanger operating under pressure [Тепловой баланс регенративного теплообменника, работающего под давлением]. Reporter of Priazovskyi State Technical University: Collection of scientific papers –Part 2. Vol. 18: pp. 141-144 (2008)
27. Koifman, A.A., Simkin, A.I.: Experimental determination of the effect of pressure on the gas-coolant heat regenerative checker. Metallurgical and Mining Industry, 4(2): pp. 107-112 (2012)