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IMPROVEMENT OF THE CONTROL PROCESS OF THE HEAT TREATMENT OF IRON ORE PELLETS IN THE PREHEATING AREA OF THE CONVEYOR-TYPE ROASTING MACHINE

The object of research is the process of heat treatment of iron ore pellets. To study it, a technological zone of pre-heating of a conveyor-type roasting machine was used. Technological process control is performed on the basis of fuzzy and incomplete information about the state of this zone. One of the main requirements regarding the functioning of the technological preheating zone is to ensure the regulatory values of the thermal and gas modes when changing the speed of movement of the conveyor belt carts. Efficiency improvement of control of these modes is provided thanks to the automatic control system, implemented on the basis of fuzzy and incomplete information on the state of the technological parameters of the zone.

In the course of the study, the analysis of scientific and technical information was carried out and the analytical method determined the importance of improving the process of controlling the thermal process of processing iron ore pellets in the technological preheating zone. On the basis of experimental studies, the features of the technological process have been taken into account, it requires the improvement of the process of controlling the operation of the technological preheating zone. The mathematical model uses the temperature of the coolant of the gas-air flow, the flow rate of natural gas and air, the temperature of the pellet bed and their mass on the carriages of the conveyor belt of the machine. At the same time, the output technological parameters of the drying zone and the input parameters of the firing zone are taken into account.

On the basis of solving systems of fuzzy functions and the principles of parametric identification, a mathematical model is proposed that approximates the dynamics of the thermal process of processing iron ore pellets in the technological preheating zone. The characteristics of transient processes of heat treatment of pellets obtained on mathematical models are analyzed taking into account the variable parameters of the adjacent technological zones of the machine, the consumption of natural gas and air. On the basis of mathematical modeling, studies have been carried out to determine the optimal distribution of the coolants of the gas-air flow over the technological preheating zone. The hardware and software for the automatic control system for the heat treatment of pellets taking into account the variable parameters of the coolants of the gas-air flows in the technological preheating zone has been implemented.

Keywords: *conveyor-type roasting machine, iron ore pellets, technological preheating zone, heat treatment, fuzzy logic.*

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1. Introduction

The technological zone (TZ) of preliminary heating (PHTZ) of pellets in a conveyor-type roasting machine (CTRM) is intended for preparation for high-temperature heating of the pellets in the technological zone of roasting (TZR), warming up the upper part of the layer and completing the drying of the lower horizons of the pellet layer. With the loading of raw pellets of the standard value and their moisture content from 9.0 to 9.2 %, the temperature in the PHTZ should be in the range from 850 to 1000 °C [1, 2]. In this case, the task of the zone is to remove the remaining moisture (no more than 5 % of the total content), partial oxidation of magnetite and limestone decarbonization, mainly in the upper horizons of the pellet layer, and on this basis, the formation of new chemical compounds due to the reaction in the solid phase. When the moisture content of the raw pellets is higher than the regulated one, it is advisable that the temperature regime ensures its removal with a moisture remainder of 25 to 30 % of the total content in the layer. In PHTZ pellets are treated with spent secondary heat carrier of gas-air flows (GAF) from the outputs of the second technological drying zone (TDZ) and TZR. Also, high-temperature combustion products of natural gas, which is burned by an injection burner, are located above each vacuum chamber PHTZ on both sides of the CTRM. Atmospheric air is supplied to injection burners by a fan to improve gas combustion. Therefore, the issues of studying the patterns and processes occurring in the PHTZ when changing the parameters of the GAF coolants and the development of assigned technical solutions that ensure their effective use are becoming relevant.

As the analysis of the research results shows, in [3, 4], this problem is highlighted and some options for its solution are given. In works [5–7], it is proved that the parameters of the GAF coolants significantly affect the heat treatment of the pellets at the CTRM, therefore, requires their diagnostics and control. TZ parameters on the production equipment are almost impossible to determine; therefore, researchers suggest using fuzzy data in process control [8, 9]. They also offer various models [10, 11] or adaptive fuzzy control systems [12, 13]. The research results of technological process (TP) control using fuzzy sets are presented in works [14–16]. Here, the rules of fuzzy inference tables are corrected to maintain a given quality of control processes when the values of the object's parameters are changed that go beyond the permissible limits. In other scientific papers [17, 18], automation of the synthesis of controllers and state observers in the MATLAB environment is presented.

The performed analysis of the scientific literature and scientific research showed that it is necessary to perform mathematical modeling of thermal, GAF and physical and chemical processes in PHTZ. Thermal treatment of pellets requires the development of a scientific basis for the creation of an innovative scheme for controlling the supply of coolants to the GAF in the PHTZ. The use of fuzzy logic algorithms allows one to split the universal sets for optimal control of the TP in the PHTZ. The results of studies of mathematical models in scientific works do not allow the development of technical solutions designed to improve the gas-dynamic characteristics in the layer of pellets and PHTZ. The mathematical models proposed by the researchers do not take into account the effect of the temperature of the GAF coolants of the neighboring zones on this process; there is no automated redistribution of the used GAF coolants. Therefore, the control of TP in PHTZ needs to be supplemented with an automation scheme.

Thus, *the object of research* is the process of heat treatment of iron ore pellets. To study it, a technological zone of pre-heating of a conveyor-type roasting machine is used.

The aim of research is to ensure an increase in the efficiency of control over the process of heat treatment of iron ore pellets in PHTZ through the development of principles, structure and study of the operation of an automatic control system based on fuzzy logic.

2. Methods of research

During the execution of the work, general scientific and special research methods were applied:
- analytical method for studying the control process of heat treatment of iron ore pellets;
- methods of fuzzy logic in the tasks of automation of thermal processes in the formation of rules of fuzzy logic for mathematical modeling of the quality of transient processes. This made it possible to control the thermal processing of the pellets in the preheating technological zone;
- method for planning an experiment and processing data for conducting experimental studies, taking into account the features of the technological process necessary to control the process of processing pellets in the technological zone of preheating;
- method of mathematical modeling to study the influence of the input parameters of the second drying zone and the output parameters of the firing zone, the temperature of the coolant of the gas-air flow, the consumption of natural gas and air. This made it possible to determine the temperature of the pellet bed and their weight on the carriages of the machine's conveyor belt.

3. Research results and discussion

Taking into account the peculiarities of the TP to control the PHTZ operation work, let's use the input plural:
- [Tsh2], [W3] and [H3] – output sets of the PHTZ second technological drying zone;
- [Tp2] – temperature of the coolant of the GAF with TZR;
- [Gv1] and [A1] – natural gas and air consumption.

The ranges for the input sets for industrial CTRM of the LURGI-278A type (Germany) at the firing site of the pelletizing plant (PP) were selected by expert assessment:

[Tsh2]=[400 700], [W3]=[3 12],

[H3]=[340 400], [Tp2]=[250 550],

[Gv1]=[150 350] and [A1]=[240 500].

Fuzzy inference is formed by determining the temperature of the upper layer of the pellets and their mass on the conveyor belt carriages. Their sets have the following ranges:

[Tsh3]=[500 1060] and [Mo1]=[2.4 3].

Using the research methodology for heat treatment of pellets in the drying technological zone and the formation of rules of fuzzy logic, are given in [3, 9], developed for PHTZ rules, one of which is presented in the following form:

Rt (PHTZ): If (Tsh2 is Z) min (W3 is Z)
min (H3 is PS) max (Gv1 is PL) and (A1 is NL)
then (Tsh3 is PL) min (Mo1 is PS).

In the MatLAB/Simulink programming environment, by adding a preheating zone ZPH to the model of the fuzzy logic controller Fuzzy Logic Controller, a simulation model of the operation of the fuzzy logic controller was created when controlling the process of preheating pellets in the PHTZ (Fig. 1).

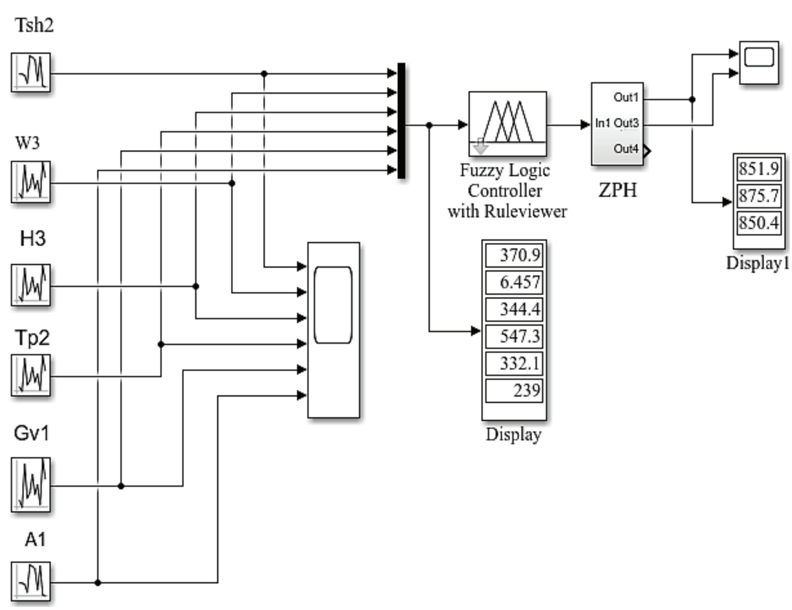

Fig. 1. Simulation model of the control system for the process of preheating pellets in the preheating technological zone based on fuzzy logic

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The specified effect is set in the form of a block of output parameters of the sets: the second drying zone [Tsh2], [W3] and [H3], and additional: [Tp2] – the temperature of the heat carrier, pumped from the TZR and to simulate the consumption of natural gas [Gv1] and air [A1] in the corresponding gas-air ratio. The model uses the output sets [Tsh3] and [Mo1]. At the output of the Fuzzy Logic Controller, a control signal is formed, which, in fact, is a corrective action, is introduced into the control system for the firing zone to keep it in a routine state.

After the synthesis of the rule base, membership functions and general inference using the «Fuzzy» subroutine in the MatLAB/Simulink programming environment, certain surfaces are a fuzzy logic regulator (FLR) for the preheating zone (PHZ). The graphs of the control surface of the phase controller for FLR are shown in Fig. 2.

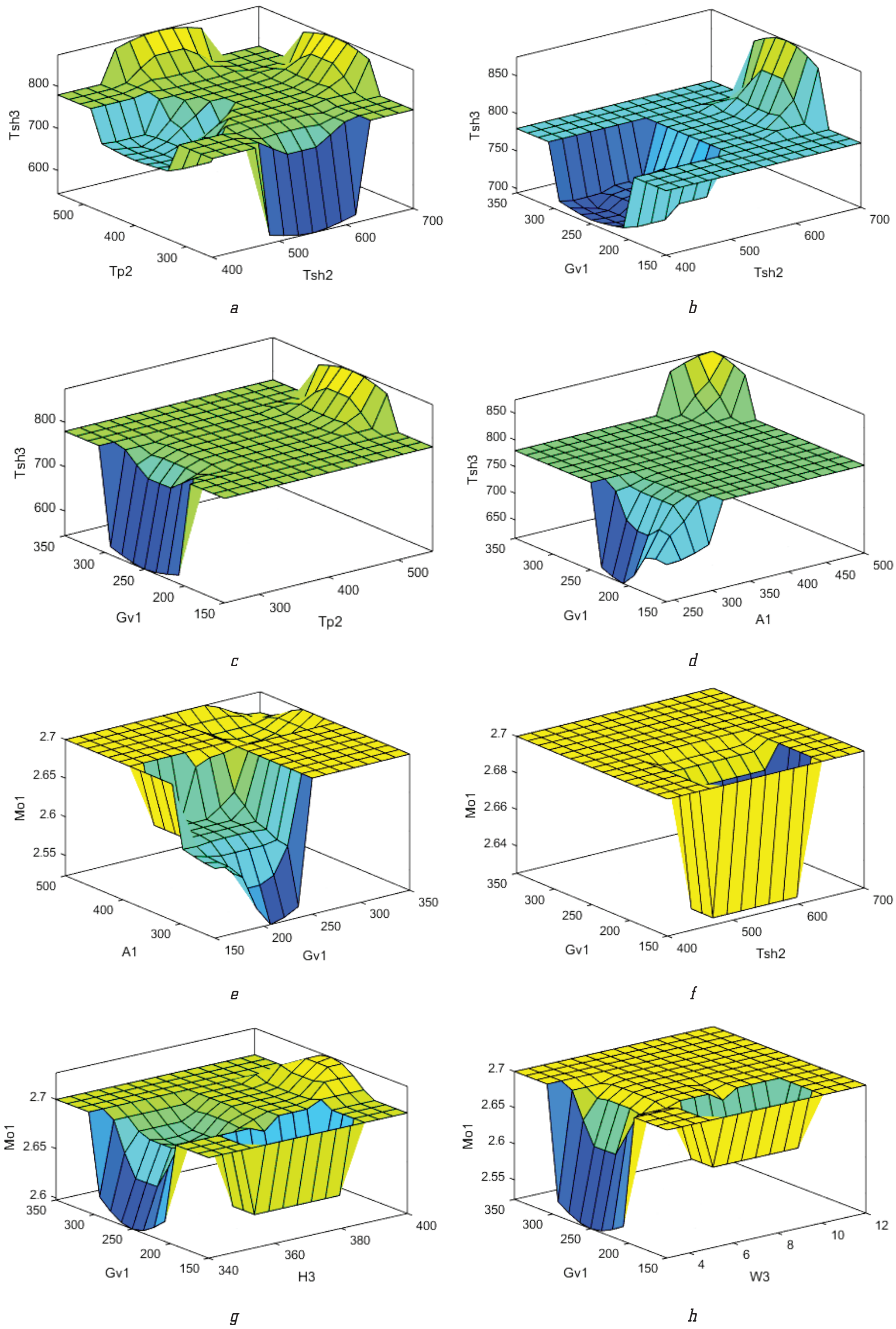


Fig. 2. Graphs of the control surface of the phase controller for the technological preheating zone:
a – [Tsh3]=*f*([Tsh2], [Tp2]); *b* – [Tsh3]=*f*([Gv1], [Tsh2]); *c* – [Tsh3]=*f*([Tp2], [Gv1]); *d* – [Tsh3]=*f*([A1], [Gv1]); *e* – [Mo1]=*f*([Gv1], [A1]); *f* – [Mo1]=*f*([Gv1], [Tsh2]); *g* – [Mo1]=*f*([Gv1], [W3]); *h* – [Mo1]=*f*([Gv1], [H3])

The research results confirm the significant influence of the parameters of the temperature of the GAF coolant from the firing zone (FZ), the consumption of natural gas and air, as well as the height of the pellet layer on the conveyor belt (CB) carts, on the temperature of the upper pellet layer in the PHZ. With an increase in the amount of combustion of natural gas and air, the temperature of the upper layer of pellets in the PHZ increases exponentially. Natural gas consumption in the ratio with air 1:5 decreased by 0.35 % after optimizing the temperature distribution of the upper layer of pellets in the PHZ in comparison with the known control systems [1, 3]. Using a simulation model of the control system for the process of preheating of pellets in the PHTZ on the basis of fuzzy logic, studies of the influence of input parameters on the output are carried out. The following sets are fed to the model input: [Tsh2], [W3], [H3], [Tp2], [Gv1] and [A1], which are shown in Fig. 3, *a*. The result of the obtained changes in the initial sets [Tsh3] and [Mo1] are shown in the graphs in Fig. 3, *d*.

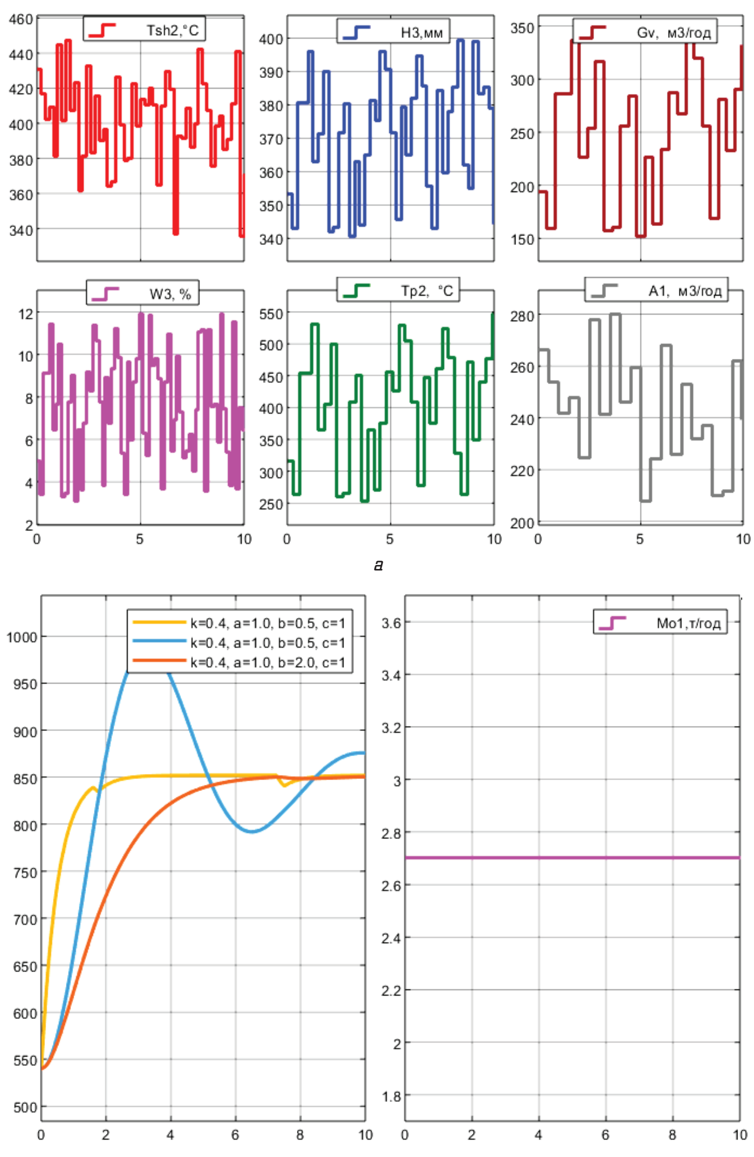


Fig. 3. Results of modeling the process of controlling the preheating of pellets in the technological zone of preheating based on fuzzy logic:
a – input sets; *b* – output sets

The model of the PHTZ control object is described in the form of a transfer function. This model was obtained on the basis of analytical calculations and experimental data. So, to determine the initial dependence of the change in the temperature of the upper layer of pellets Tsh3=$f(t)$, the PHTZ is represented by three links:

– 1 – aperiodic:

$$W(s)=\frac{0.4}{s+1};$$

– 2 and 3 – vibrational respectively:

$$W(s)=\frac{0.4}{s^2+0.5s+1} \quad \text{and} \quad W(s)=\frac{0.4}{s^2+2s+1}.$$

The research results showed that the shortest time of 2 s, at which the transient process ends, for the temperature of the upper layer of the pellets is shown in Fig. 3, *a*. The time of the transient process when using an oscillatory link ends in 6 s (Fig. 3, *b*). With a doubling of the time constant of the oscillatory link, an oscillatory process of changing the temperature of the pellet layer occurs and the time of the transient process increases. The output sets for the mass of the pellets [Mo1] remain unchanged over time.

To determine the effect of the temperature of the GAF coolant with FZs on the output functional dependencies of the PHZ, modeling was carried out with changes in the temperature of the GAF coolant: minimum from 200 to 300 °C, average 400–450 °C and maximum 500–600 °C. For this, simulation of the assembled Simulink –models.

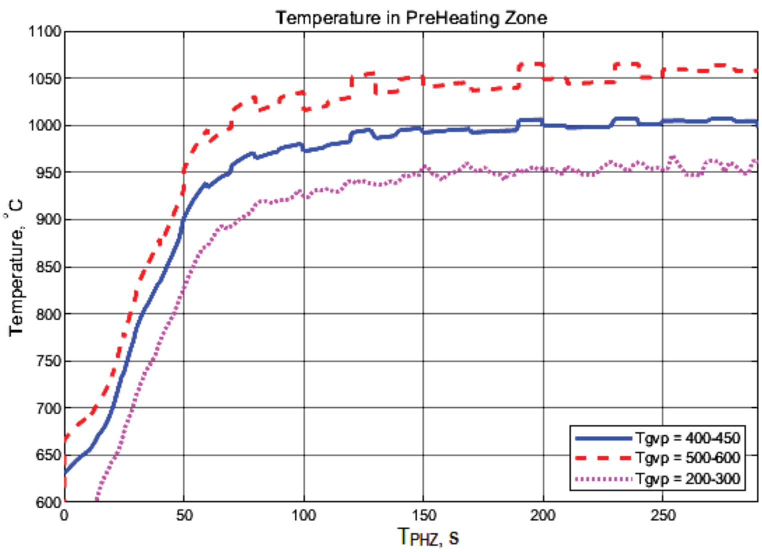
The simulation result is shown in Fig. 4, in which the time interval (T_{PHZ}) in the PHTZ is 290 s.

According to the graphs shown in Fig. 4, *a*, the temperature characteristic changes according to the aperiodic law at a given temperature range from 600 °C to 1000 °C. They have a certain time lag, as well as deviating fluctuations, are ±5 °C.

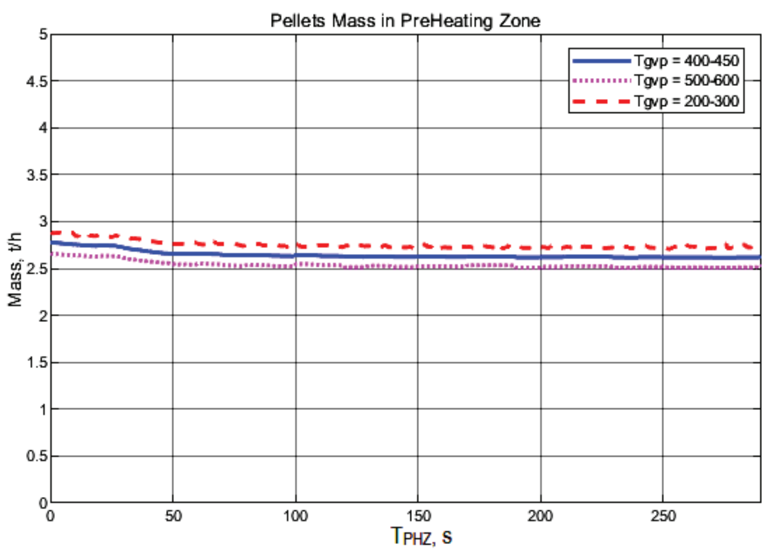
With the maximum temperature spread of the coolant from 500 to 600 °C, the graph proportionally increased by 50 °C, and the fluctuations by 5–10 °C. With the minimum temperature spread of the coolant from 200 to 300 °C, the characteristic decreased proportionally by 50 °C, and fluctuations take on values of ±3 °C. The characteristic change in mass (Fig. 4, *b*) decreases throughout the entire PHTZ zone with an average value of 2.6 t/year, since the final moisture and some impurities burn out.

The value of the mass of the pellets was empirically calculated for the length L and width W of the bogie KS with the height H of the pellet layer on it, taking into account the coefficient 2.17 of the bulk mass of the pellets, which was determined from experimental data, according to the following formula:

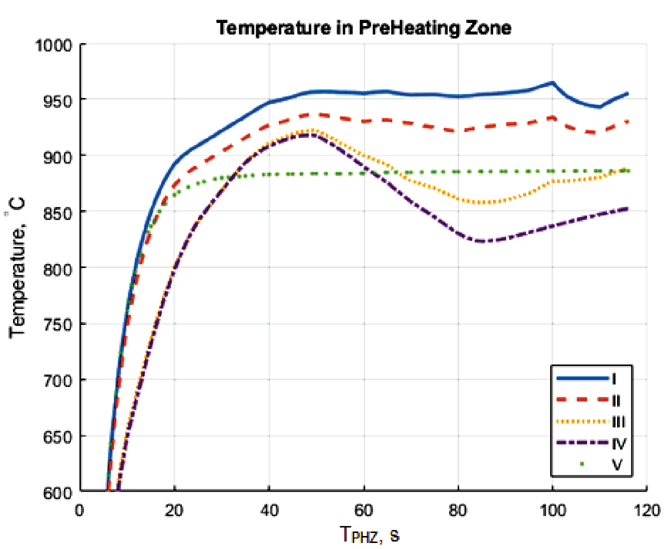
$$m=L\cdot W\cdot H\cdot 2.17.$$



a



b



c

Fig. 4. Simulation results for the scatter of the coolant temperature values, the gas-air flow for the technological preheating zone: *a* – temperatures of the upper layer of the pellets; *b* – mass of the pellets on the carts of the conveyor belt; *c* – if some input sets are not taken into account

The accounting for the mass of the pellets on the bogies KS is carried out taking into account the initial bulk weight of the green pellets with the TZR. With the maximum and minimum scatter in the temperature values of the CAS coolant, respectively, from 200 to 300 °C and from 500 to 600 °C for the PHTZ, the mass of the pellets changes by 0.1 t/year, as a result of the processes indicated above.

A series of experiments was carried out with changes in the input sets of the PHTZ model. The influence of these sets on the output characteristics is revealed. For this, at each stage, fuzzy sets were not taken into account: the temperature of the CAS coolant, the height of the layer and the moisture content of the pellets. The simulation result is shown in Fig. 4, *c*, which indicate the characteristics:

– taking into account the following sets: I – [Tsh2], [W3], [H3], [Tp2], [Gv1] and [A1];

– without taking them into account: II – [Gv1], III – [Gv1] and [Tp2], IV – [Gv1], [Tp2] and [H3], V – no input sets.

The second characteristic does not take into account the consumption of natural gas in comparison with the first, when all input sets are taken into account, has a significant subsidence behind the temperature indicator, but is smoother and has insignificant hopping deviations. Characteristic III, when the consumption of natural gas and the temperatures of the GAF heat carriers, which are supplied from the pollutants, are not taken into account, also increases aperiodically in the time interval from 50 s to 90 s. There is also subsidence, which shows a significant effect on the temperature characteristics of moisture indicators and the height of the pellet bed on the KS bogies. The next characteristic IV, which, in comparison with III, additionally does not take into account the height of the pellet layer, is similar to the previous form. However, it should be noted that the characteristic has a significant subsidence in the temperature characteristic and does not get the temperature value specified in the regulations. If one of the input parameters is not taken into account, then the characteristic V will have a general aperiodic character without drawdowns and jumps, but it is not adequate and does not provide the temperature value specified by the regulations.

4. Conclusions

The issues of improving the control process for the heat treatment of iron ore pellets in the technological zone of preheating of the conveyor-type roasting machine are considered. Based on the solution of systems of fuzzy functions and the principles of parametric identification, mathematical is improved model that approximates the dynamics of the thermal process of processing iron ore pellets in the technological preheating zone. A feature of the mathematical model is that it takes into account the variable technological parameters of the adjacent technological zones of the machine, iron ore pellets, natural gas and air consumption. The characteristics of the transient processes of heat treatment of the pellets obtained in the course of modeling are analyzed and a study is carried out to determine the optimal distribution of the coolants of the gas-air flow over the technological preheating zone. It is shown that the temperatures of the GAF coolant and the upper layer of pellets with PHTZ, the consumption of natural gas and air have the greatest effect on the PHTZ output characteristics. It has been determined that with an increase in the amount of combustion of natural gas and air, the temperature of the upper layer of pellets in the PHTZ increases exponentially. When optimizing the routine distribution of the temperature of the upper layer of pellets in the PHTZ in comparison with the known control systems, the PHTZ made it possible to reduce the consumption of natural gas by 0.35 % at an air flow rate of 1:5. The hardware and software of the automatic control system for the heat treatment of pellets was implemented taking into account the variable parameters of the heat carriers of the gas-air flows in the technological preheating zone.

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