*Наведено результати дослідження зміни температури газоповітряних потоків на виході із зони випалювання і рекуперації конвеєрної випалювальної машини. Визначено вплив цих температур на інші технологічні зони.*

*Показано, що середньооб'ємні значення температур газоповітряних потоків із зон випалювання і рекуперації є експоненціальними залежностями від температур газоповітряних потоків над шаром обкотишів у цих зонах. Встановлено, що збільшення швидкості переміщення випалювальних візків від 0,011 м/с до 0,06 м/с приводить до зменшення у 1,7 рази середньооб'ємного значення температури нагрітого газоповітряного потоку. Збільшення висоти шару обкотишів на випалювальних візках на 30 відсотків при постійній газопроникності цього шару приводить до зменшення по експоненціальному закону середньооб'ємну температуру газоповітряного потоку в 2,5 рази на виході із зон випалювання і рекуперації. При зміні тиску в зоні випалювання на 20 %, постійній швидкості переміщення випалювальних візків 0,049 м/с, висоті шару обкотишів 450 мм і пористості шару обкотишів рівною 0,45 $м^3/м^3$ середньооб'ємні температури газоповітряних потоків на виході з шару обкотишів зменшуються до трьохкратної величини.*

*Для аналізу температурного режиму газоповітряного потоку на виході зони випалювання обкотишів використано математичну модель. В основі математичної моделі враховано, що входи і виходи технологічних зон машини пов'язані рівняннями газодинаміки, теплообміну і масообміну.*

*Дослідження дозволило розробити і представити автоматизовану систему управління димотягами за середньооб'ємними температурами газоповітряних потоків на виході із технологічних зон випалювання і рекуперації, яка може бути використана в промислових умовах.*

*У результаті забезпечується покращення термічного процесу та газодинамічної роботи технологічних зон конвеєрної випалювальної машини*

*Ключові слова: конвеєрна машина, технологічні зони, шар обкотишів, температура, тиск, керування газоповітряними потоками*

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# DETERMINING THE INFLUENCE OF PARAMETERS FOR GAS-AIR FLOWS ON THE THERMAL PROCESS OF PRODUCING IRON ORE PELLETS

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## 1. Introduction

Conveyor plants (CP) are complex energy systems, which provide a thermal process for production of iron ore pellets. Such technological plants belong to the most energy-intensive plants.

At present, there is a need to ensure maximum production of iron ore pellets at CP with high quality and lower energy consumption. This affects substantially the cost of finished products of the treatment plant of ore-dressing and processing enterprise.

The most important direction of energy saving is the economical burning of fuel and the rational use of gas-air flows in production of iron ore pellets. The processes of temperature and gas-dynamic modes, which operate in each zone of CP, significantly affect production of pellets. Additionally, their energy consumption changes during transportation, drying, preheating, calcination, and cooling.

It is necessary to observe a temperature range and time of treatment in each zone strictly to obtain the finest quality materials at production of iron ore pellets. There are other parameters, which affect the structure and durability of calcined pellets in addition to parameters of the thermal process for treatment of pellets, which determine parameters of CP zones. These parameters include support of uniformity of processes of drying, preheating, calcination, and cooling of an entire layer of pellets. It can be achieved by maintaining the required temperature of gas-air flow over CP zones. Therefore, these are the relevant issues to study the patterns and processes, which occur in each technological zone, and especially improvement of gas-dynamic characteristics of CP.

There is no full control of the observance of gas-dynamic and temperature characteristics at CP in its technological zones at production of pellets due to the practical impossibility of direct measurement of temperature in a layer of pellets in calcination carts. Therefore, we have to control the thermal process of production of pellets based on non-direct determination of temperature of pellets [1]. Experts carry out studies in this area and there are new developments in this field. The works devoted to investigations that significantly affect the efficiency of drying, calcination, and cooling zones of CP, confirm achievement of new developments [2–4]. This indicates that additional research is necessary to clarify redistribution of gas-air flow parameters over CP zones. It is necessary to take into consideration its value at the changes of the speed of movement of calcination carts, of the height of a layer of pellets on them, etc. Taking into consideration such changes will provide an efficient gas-dynamic mode in CP zones and, as a result, fabrication of quality products. That is, this approach shows also that the study topics devoted to the thermal process of production of pellets at CP with the control of gas-air flow parameters is an actual scientific and practical task.

## 2. Literature review and problem statement

Paper [5] presents the results of studies on two-level system of optimization of the mode of heat treatment of pellets. It shows that periodical solution of the problem of static optimization of the mode based on mathematical models of technological zones occurs at the upper level. At the same time, estimation of parameters of a pellet layer and stabilization of the optimal mode of heat treatment occurs at the lower level. But there are still unresolved issues related to the failure to take into consideration parameters for determination of the influence of gas-air flows on technological zones of CP in mathematical expressions of the model. The reasons for this are the difficulties associated with measurement of parameters of gas-air flows in CP technological zones. An option to overcome the difficulties may be the studies and their results presented in paper [6]. It proposes the thermal model of the calcination process of pellets to determine temperature distribution by the height of a layer in separate zones of CP. It establishes basic dependencies and thermophysical properties of material. They are source data for modeling of the process.

However, the model does not solve the issue of maintenance of the given parameters of gas-air flows over CP technological zones. There is a comparative analysis of modern heat engineering schemes of conveyor calcination plants for heat treatment of iron ore pellets in work [7]. It shows that each of the analyzed schemes has reserves for improvement of performance. But it does not consider the issue of management with existing draught devices, which would provide saving of gas and heat energy. A decrease in the average consumption of natural gas by 2 $m^3$/year is possible at using of the control system of the thermal process of pellet production with a fuzzy controller [8]. Simultaneous introduction of atomic-emission spectroscopy to this system increases the efficiency of CP by 2.5 %, due to more uniform gas permeability of a layer of pellets, which leads to an increase in the rate of filtration of a gas flow and intensification of the heat transfer process in a layer of pellets. But the issue of the influence of gas-air flows from one technological zone to the other zone remained unresolved. The mathematical model used in a fuzzy controller system does not take into consideration changes in parameters of gas-air flows that affect the quality of pellets.

Paper [9] presents the research results on using of temperature distribution in a layer of pellets in the technological calcination zone in the model. The model simulates the processes of heat exchange and thermal irradiation by the height of a layer of pellets. However, the model does not take into consideration the change in parameters of the gas-air flow, which leads to significant errors in determination of the parameters of the thermal mode of pellets in the calcination zone of CP. All mentioned leads to a decrease in CP performance. According to work [10], the main parameter that practically determines the performance of CP is the coefficient of resistance of a layer of pellets. Therefore, to determine the gas-dynamic state of a layer, it is expedient to use the semi-empirical Darcy-Weisbach equation, which is widely used in spherical gas dynamics. We can use this approach to determine parameters of gas-air flows at the outlets of technological zones. However, it is not possible to use this approach for determination of redistribution of these flows over CP zones.

Other works notice, that such technology of treatment of iron ore pellets at CP, which contain charge materials, has a number of difficulties and features [2, 4]. They include significant energy costs at non-rational use of gas-air flows. In addition, there is no possibility to control temperature of a pellets layer in real time when calcination carts move through CP technological zones [6, 9, 10]. All this leads to a low-quality thermal process in production of pellets. However, it is not possible to solve the intensification of heat exchange in a layer of pellets by control of the speed of movement of high-temperature gas-air flows, their parameters depend on the height of a layer and the power of smoke exhausters. The results of other studies [4, 11] show that there is no optimum height of a layer of pellets by productivity on calcination carts of CP at all values of discharge in vacuum chambers of technological zones. Thus, the optimum height of raw pellets should be 0.45–0.48 m at a discharge of about 4.5 kPa in vacuum chambers of technological zones with high temperature, and it should be 0.5–0.55 m together with the “bed”, but it does not hold in the specified ranges.

However, we should note that this work does not consider possibility of using of automated systems to control redistribution of gas-air flows in technological zones of CP. This means that it does not determine fully how the process of changes in parameters of a gas-air flow proceeds in CP zones.

Scientific works [2, 6, 11] recommend to use optimal modes of the thermal process, which give possibility to obtain iron ore pellets with high metallurgical properties. They propose mathematical models for control of the process of production of pellets at CP. In this case, the mathematical models do not take into consideration the influence of parameters of gas-air flows on the thermal process and do not solve the issue of redistribution of these flows in technological zones of CP.

Except for the analysis of the behavior of thermal processes on mathematical models, researchers look for ways to improve the quality of iron ore pellets and to increase productivity of CP on these models [12–16]. Thus, the automatic control system for thermal treatment of pellets at CP provides adaptation of known models and control algorithms to changes in parameters of an object and external influences in paper [12]. The models take into consideration speed of tape movement, height of a layer, gas consumption, speed of blowing, humidity, and an average diameter of pellets, basicity, and composition of iron in pellets. This increases the CP productivity by 2.5 %. However, there are problems with real-time measurement of technological parameters in a flow.

For example, what is the temperature inside a layer of pellets on calcination carts. It does not take into consideration distribution of heat of gas-air flows in CP zones. The behavior of the process leads to obtaining of low-quality pellets and excessive consumption of natural gas.

Papers [14, 15] propose new technologies in scientific researches devoted to methodologies of system analysis and procedures for the use of mathematical modeling of thermophysical processes in metallurgy [14, 15]. These papers provide possible ways to improve technical and economic performance of CP. The papers propose further modernization of existing automated systems for control of process of calcination of pellets in the direction of optimization of the technological mode. Authors use the modern theory of automatic control, but they do not consider the process of pellets production fully. The models proposed do not take into consideration the influence of temperature of gas-air flows of adjacent zones on the process of pellets production.

Disadvantages of the models presented in works [13, 16] include neglection of the heat exchange between raw pellets and calcined ones, located along the perimeter of calcination carts, and between pellets and carts. The models do not take into consideration the influence of temperature of a gas-air flow, which goes from the calcination and recuperation zones to drying and preheating zones, on the thermal process of pellets production.

Studies performed in paper [17] made it possible to establish necessity of differentiated stacking of pellets by the height of a layer to exclude unevenness of their heat treatment. The paper proposes the construction of roll vibration screen, which provides the necessary segregation of granules along horizons. However, authors do not consider the question of how a gas-air flow influences the thermal process with such stacking of pellets.

Paper [18] presents a mathematical model of the process of calcination of ore-coal pellets at CP. The structure of ore-coal pellets is a sphere, which consists of evenly distributed granules of ore, limestone and fuel, in the model. The bases of the radii of the spheres are possibilities of mill equipment, which limits application of this model significantly. Work [19] presents the results of the dynamic modeling of processes of induction of granules in a direct-flow system. The known models do not take into consideration distribution of heat and the effect of the speed of a gas-air flow on the process of pellets production. The model does not calculate a change in the internal energy of each of interacting pellets. Authors of the work did not calculate the amount of air required for full combustion of natural gas, which would ensure its more rational use. The model does not give possibility to determine a change in temperature of a gas-air flow during the passage of a layer of pellets. The main advantage of other mathematical models is optimization of the calcination process of pellets by separate zones of CP [20, 21]. However, the proposed optimization of thermal treatment of pellets does not make it possible rational use of gas-air flows over technological zones of CP. Taking into consideration the effect of these flows, it practically leads to a decrease in specific energy consumption.

In addition, it is necessary to perform additional transformations to switch from heat amount to specific temperature values in the technological zones of calcination and recuperation. Scientists investigate a decrease of pressure of a flow in a dense layer by the height and the change in the radii of pellets using mathematical models [20–23]. Researchers do not consider influence and redistribution of parameters of gas-air flows on technological zones and along a whole CP in the mentioned models. Non-definition of these parameters leads to low-quality thermal process of pellets production. The presented results of studies in these scientific works do not give possibility to develop technical decisions intended to provide improvement of gas-dynamic characteristics in a layer of pellets and technological zones of CP. Other researchers analyze the effect of the coefficient of gas-dynamic resistance of a layer of pellets on the thermal process of pellets production [24]. As we know, porosity of a layer of pellets varies from zone to zone, so gas-air flows change significantly when passing through a layer of pellets in each technology area. This leads to a change in the thermal process of pellets production of CP. There are not regularities of gas-air flow parameters change taking into consideration the coefficient of gas-dynamic resistance of a layer of pellets in this scientific work.

The works by authors who study gas dynamics of flows on mathematical models and simulate cooling of a layer of pellets, or investigate a decrease in pressure in a dense layer are of particular interest [25–27]. Some models complicate adsorption and desorption processes [28]. Researchers use predictive ANFIS-models [29] to control the temperature mode of the calcination process in most modern studies. However, known models do not give a complete picture of distribution of a gas-air flow through CP zones.

We did not find research results, which improve the energy efficiency of gas-dynamic characteristics during the thermal process of production of pellets. Therefore, there are reasons to believe that there is a lack of certainty of the influence of parameters of gas-air flows supplied from the technological zones of calcination and recuperation to other zones. And there is no definition of the influence of atmospheric air on the thermal process of pellets production. It is possible to assume that control of gas-air flow parameters can increase not only the quality of the heat treatment process of iron ore pellets, but also decrease consumption of natural fuel and an amount of harmful emissions into the atmosphere. The provision of the best gas-dynamic characteristics for CP necessitates the study in this direction.

## 3. The aim and objectives of the study

The aim of this study is to investigate a change in parameters of gas-air flows at an outlet of technological zones of calcination and recuperation of CP with determination of possibility of control of the thermal process of production of iron ore pellets in the function of a change in temperature of gas-air flows, which go out of these zones.

We set the following tasks to achieve the objective:

– to determine parameters of gas-air flows, which go out of the technological zones of calcination and recuperation and affect the thermal process of pellets production at CP and, based on these definitions, development of a structural diagram of the control of the smoke exhausters for control of the thermal process of pellets iron ore production at CP;

– to determine the distribution of temperatures of gas-air flows in the technological zones of CP during control of smoke exhausters in the functions of medium-volume temperatures of gas-air flows, which go out the technological zones of calcination and recuperation.

## 4. Determination of parameters of gas-air flows, which influence the thermal process of pellets production at CP

It is necessary to remember that CP operates under different modes, loads, diverse disturbances, with raw materials and energy carriers, which have different characteristics to find parameters of gas-air flows going out from the technological zones of calcination and recuperation. Changes in these characteristics leads to fluctuations in the aerodynamic resistance of a layer of pellets, which, in turn affects a number of vacuum chucks under calcination carts, and, accordingly, parameters of a gas-air flow under them, breaking gas permeability of a layer. For these reasons, maintenance of the scheduled mode of the thermal process of pellets production at CP must occur taking into consideration parameters of gas-air flows and determination of an amount of air supply.

Researchers improve the automated control systems of the thermal process in separate technological zones are improved, widely using various algorithms of operation and mathematical models, for a more qualitative course of the thermal process of production of iron ore pellets at CP. They use the results of experiments, statistical tests, expert evaluation and results of complex calculations as source data. Let us consider the following source data depending on a type of CP. The height of the layer of pellets on calcination carts keeps at a level from 0.32 to 0.5 m, and the diameter of pellets varies from 5 to 16 mm with moisture content in the range from 8.8 to 10.8 %. The fluctuation of the load of the layer of raw pellets on calcination carts reaches 20 % at a productivity of 250 t/h, which are approximately 55–85 kg/s. This causes an uneven height of the layer of pellets [3, 15]. The speed of movement of calcination carts changes along the technological zones of CP from 0.5 to 5.6 m/min, respectively, depending on the mentioned load fluctuation.

The thermal process of pellets production at CP practically depends on the speed of filtration (movement) of a gas-air flow through a layer [15, 17]. The speed value closely interacts with gas permeability through a layer of pellets. The speed of air filtration depends on parameters of pellets in a layer and a value of dilution under calcination carts. Therefore, with the transition to a new technology, for example, the baking of pellets with an increase of the height of a layer to improve performance of CP goes before reconstruction of a smoke exhauster, increasing power of their motors. We know that an increase in vacuum is associated with an increase in the cost of electricity and air, and compaction of CP requires significant additional capital costs.

Therefore, it is now better to devote time to research aimed at the rational use and management of parameters of gas-air flows and timely delivery of atmospheric air in the technological zones of CP. Smoke exhausters provide this control. In this case, the automated control system for smoke exhausters must take into consideration parameters of gas-air flows, technical and technological parameters of CP and pellets. There are various structures of thermal engineering schemes of CP, as indicated in works [2, 7]. However, it is possible to improve their performance by control of parameters of gas-air flows in the function of a change in the temperature of a gas-air flow, which goes out from the zones of calcination and recuperation. To do this, it's enough to use automated control of the smoke exhausters, which can operate by different algorithms and models. In addition, due to rational management of supply of atmospheric air, which enters the calcination zone through the cooling zone, by smoke exhauster, we can provide optimal gas-dynamic characteristics in this and other CP zones. This changes the quality of the heat treatment process, reduces energy consumption and reduces an amount of harmful emissions into the atmosphere.

## 5. Development of the structural scheme of the automated control system of smoke exhausters of CP

We developed an automated control system (ACS) of smoke exhausters for the effective automatic control of distribution of gas-air flows at CP in the function of changes in parameters of a gas-air flow, which goes out from the zones of calcination and recuperation. Fig. 1 shows the structural heat engineering scheme of CP and ACS. The scheme consists of the following structural elements: E1, ..., E5 – smoke exhausters, GC – gas cleaning, CU1, ..., CU3 – control units, TS1 and TS2 – temperature sensors, $S_{hp}$ – a sensor of the height of pellets, $S_{sp}$ – a speed sensor of calcination carts movement.

Pellets on the calcination carts move sequentially through the zones: drying zones – 1 and 2, preheating zone – 3, calcination zone – 4, recuperation zone – 5 and cooling zones – 6 and 7. There is air fed into cooling zone 7. This air is heated as it passes through a layer of heated pellets and cools them, then it goes to cooling zone 6. The gas-air flow heated to 900 °C is pyritic, is goes to the following zones: recuperation 5, calcination 4, preheating 3 and drying 2. At the same time heating of the gas-air flow to 1,300 °C occurs in the calcination zone due to burning of natural gas. There are burners to burn the gas. The gas-air flow heated to this temperature goes through the layer of pellets and brings them to calcination. The gas air flow of cooling zone 7, fed into preheating zone 3, removes the residual moisture from pellets. The smoke exhauster E6 supplies the gas air flow to drying zone 2 after passing through the layer of pellets in calcination zone 4. In drying zone 1, the gas air flow enters the pellets layer by blowing it from below into section 1 and suction from the top to section 2.

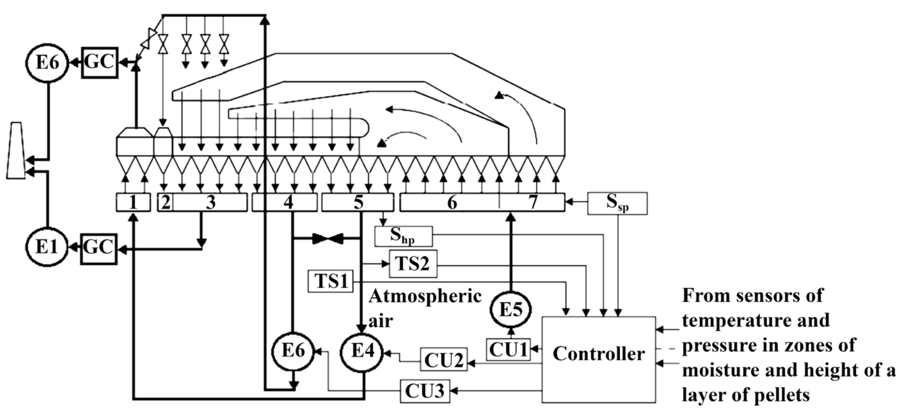



Fig. 1. ACS with smoke exhausters by the temperature of gas-air flows, which come from the technological zones of calcination, recuperation and cooling of CP

Implementation of a technical solution aimed at the transfer of the maximum amount of coolant from the cooling furnace to the pipes of the heating zone occurs by direct flow. The high-temperature gas-air flow from cooling zone 7 of CP goes to calcination zone 4 through D5, the low-temperature flow – to zone of drying 1 and preheating 3. The transfer of the gas-air coolant from one low pressure zone to another one by direct flow makes possible maximization of the amount of fuel and electricity consumption. The implementation corresponds to the heat engineering scheme with a double-flow intersection collector implemented on the smoke exhausters marked as D6 and D4. The choice of dilution in D6 and D4 collectors occurs in such a way as to provide the minimum required pressure difference from 50 daPa to 70 daPa. This is necessary for organization of suction to D4 path. Also, there are possibilities of operation of smoke exhausters at the temperature of the coolant along D6 and D4 passes taken into consideration in order to exclude division of the flow by atmospheric air in order to reduce temperature.

ACS runs the following algorithm.

There are the required ranges of temperatures and pressures of gas-air flows for the technological zones of CP set at the inlet of the controller. The controller manages E4 and E6 smoke exhausters by CU2 and CU3 control units, providing an optimal supply of gas-air flow to zones of drying 1, and preheating 2, respectively. We can control average-volume values of temperature of gas-air flows, which come from zones of calcination 4 and recuperation 5 of CP, and regulate the pressure supply of gas-air flows in drying zones 1, 2 and preheating zone 3 by E4 and E6 smoke exhausters. The system takes into consideration the height of a layer of pellets on calcination carts. $S_{hp}$ sensor determines the height. It also takes into consideration the speed of movement of calcination carts over CP zones. $S_{sp}$ sensor controls the speed. Thus, the regulation of the gas flow between zones of drying 1 and preheating 2 occurs. It provides a given temperature mode in these zones.

TS1 and TS2 sensors determine temperature of gas-air flows, which come from calcination zone 4 and recuperation zone 5, control the supply of atmospheric air to calcination zone 4 through cooling zone 7 and control the performance of E5 smoke exhauster by CU1 control unit. This makes it possible to achieve the uniformity of sintering of pellets in calcination area 5 by the height of a layer of pellets.

We assume stabilization of temperature of gas-air flows in each technological zone of CP with minimal deviations from the given values as the technological objective of control of the temperature mode of thermal treatment of pellets. Therefore, the operation algorithm ACS of smoke exhausters takes into consideration non-stationarity of parameters of the process of thermal treatment of pellets. Thermal treatment implies fluctuations in physical and chemical composition and in porosity of a layer of pellets, as well as a change in parameters of the technological equipment, etc. A specially developed algorithm compensates the great inertia of thermal processes during the control process. For implementation of compensation, the base of the algorithm of ACS of smoke exhausters is application of operational evaluation of parameters of the process and the use of adaptive predictive control of the processes of thermal treatment of pellets. This ensures improvement of the quality characteristics of pellets and reduces the specific costs of energy carriers.

We propose to perform practical implementation of the structural scheme of the automated control system of smoke exhausters of CP on a modern element base. We can use Zelio Logic20BX/B smart relay produced by Schneider Electric or other type of relay as a controller. Control units CU1,..., CU3 require vector-type frequency converters, for example, converters of HYUNDAI N5000 type. Measurement of temperatures of gas-air flows goes with the use of pyrometers or infrared thermometers. We propose to determine the speed of movement of calcination carts in the zones of CP using a contactless speed sensor. It is necessary to use smart impulse radar laser sensor to measure the height of a layer on calcination carts along the technological zones of CP. The smart high-precision excess/absolute pressure sensor measures gas-air flow pressure.

## 6. Distribution of temperature of gas-air flows over the technological zones of CP at the control of smoke exhausters in the function of temperature of gas-air flows

We must take into consideration the rate of filtration through a layer of pellets $V_0$, m/s; density ρ, kg/m$^3$ and pressure difference $\Delta P$ of a gas-air flow before entering a layer of pellets and after it, Pa to determine the temperature of the gas flow at the outlet of the calcination zone of CP. The following coefficients affect this temperature: $K_l$, which expresses an influence of a shape and size of pellets in a complex manner, and β volume expansion of gas K$^{-1}$. Taking these parameters into consideration, the interpretation of the Darcy-Weibah formula will determine the average mass temperature of a pellets layer at the outlet from the zone ($\theta_{spo}$):

$$\theta_{spo} = \left( \frac{\Delta P}{\frac{\left(K_l V_0^2\right)}{2} \cdot \rho} - 1 \right) \frac{1}{\beta}. \quad (1)$$

We use formula (2) to find the coefficient $K_L$ in the formula (1):

$$K_L = 4 \cdot \psi_L \cdot \frac{H}{d}, \quad (2)$$

where $\Psi_L$ is the coefficient of gas-dynamic resistance, (Pa·m·s²)/kg; $H$ is the height of a pellets layer, m; $d$ is the equivalent diameter of a pellet, m. We define the diameter as follows:

$$d = k_f \frac{\varepsilon}{1-\varepsilon} d_{cp},$$

where $k_f$ is the coefficient of a shape of charge particles (for a ball $k_f$=2/3); $d_{cp}$ is the average diameter of particles of furnace, m; ε is the porosity of a layer of pellets, m$^3$/m$^3$.

The coefficient $\Psi_L$ of gas-dynamic resistance for a layer of iron ore pellets depends on the Reynolds number of pellets. Therefore, we use the formula of the approximate value given in [30], it is well consistent with the experimental data by other authors:

$$\psi_L = \frac{3200}{R_e}, \quad (3)$$

where $R_e$ is the Reynolds number, which varies from 170 to 2,000.

However, this dependence is suitable for layers with a narrow porosity range ε=0.45–0.50 $m^3/m^3$. A wide range of fractions represents the granulometric composition of iron ore pellets in real conditions; therefore, gas permeability of a layer of pellets will be lower.

CP requires the continuous supply of a gas-air flow necessary for combustion of fuel and removal of produced combustion products for normal uninterrupted operation. Smoke exhausters supply atmospheric air to CP zones and remove combustion products from CP zones is carried out by smoke exhausters. Mathematical expressions given in [2, 17, 24] determine the main parameters, which determine the choice of smoke generators are their required performance, costs, pressure and pressure of a gas air flow, etc.

In the study of redistribution of temperature of gas-air flows in the technological zones CP, we assume that the initial characteristics for each subsequent zone are the outputs of the previous CP zone. We also take into consideration that the parameters of the technological zone change: a length of the zone $L$, the area of the pellets $S$, through which a gas-air flow is pumped. We also consider a change of the height of a pellets layer from the zone to the zone. We take into consideration heat of combustion of gas in the combustion zone additionally.

The inputs of the models for each technological zone of CP are: average mass temperature of a layer of pellets at the inlet to the zone ($\theta_{spi}$); average mass moisture of a layer of pellets ($U_{spi}$) (only for the drying zone and the preheating zone); speed of movement of calcination carts ($V_{cc}$); an equivalent diameter of pellets ($d$); a difference in pressure of a gas-air flow when passing through a layer of pellets ($\Delta p$); temperature of a gas-air flow, which comes to a layer ($\theta_{gai}$).

The outputs of the models for each zone of CP are: average mass temperature of a layer of pellets at the outlet of a zone ($\theta_{spo}$); average mass moisture of a layer of pellets ($U_{spo}$) (only for the drying zone and the preheating zone).

We choose the basis for a general mathematical model taking into consideration that inputs and outputs of technological zones of CP are connected by equations of gas dynamics, heat exchange and mass transfer. We will use this model further to control distribution of gas-air flow, which comes from the calcination zone of CP into other zones. We use the system of mathematical expressions given in [20] for mathematical models of the calcination, recuperation and cooling zones at control of gas-air flows at CP:

$$\begin{cases} V_0 = \dfrac{-150\mu \cdot a + \sqrt{(150\mu \cdot a)^2 + 7\rho \cdot b \dfrac{\Delta\rho}{1{,}3H}}}{3{,}5\rho \cdot b}, \\ Q = V_0 \cdot S \cdot \varepsilon \cdot \dfrac{L}{V_{AA}} \cdot C_{GAF}\left(\theta_{gai} - \theta_{gao}\right), \\ \theta_{gao} = \theta_{gai} + \dfrac{k \cdot Q \cdot V_{cc}}{L \cdot G_{coi} C_O}, \end{cases} \tag{4}$$

where μ is the dynamic viscosity of a gas-air flow; $a$ and $b$ are the estimated coefficients depending on a size and shape of pellets; $Q$ is the supply of heat from gas-air flows of other zones to pellets; ε is the porosity of a layer of pellets; $k$ is the coefficient of heat consumption spent on pellets heating; $G_{\text{COBX}}$ is the consumption of coolant for heating of pellets; $C_o$ is the specific heat capacity of pellets; $C_{\text{GAF}}$ is the specific heat capacity of gas-air flows.

The moisture of a layer is equal to zero for the technological zone of calcination and the subsequent zones. This moisture was previously evaporated by a low-temperature gas-air flow in the drying and preheating technological zones. Therefore, we supplement the system of mathematical expressions (4) of the mathematical models of drying and preheating zones at control of gas-air flows over CP zones with the equation (5):

$$U_{spo} = U_{spi} - \frac{(1-k) \cdot Q \cdot V_{cc}}{L \cdot G_{coi} \cdot \lambda}, \tag{5}$$

where $k$ is the a coefficient of heat spent on heating of pellets; λ is the specific heat of evaporation of water.

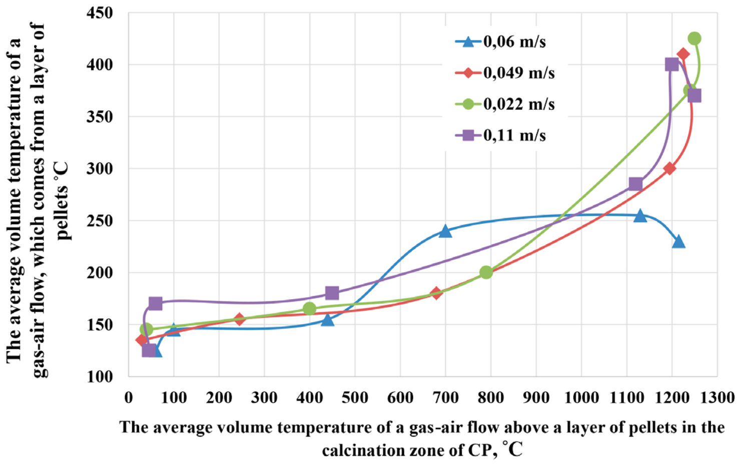
We assumed that the output characteristics of the flows for each subsequent zone are the outputs of the previous technological zone in the study of redistribution of gas-air flow parameters in the technological zones of CP.

## 5. Investigation of parameters of gas-air flows, which go out from the technological zones of calcination and recuperation of CP

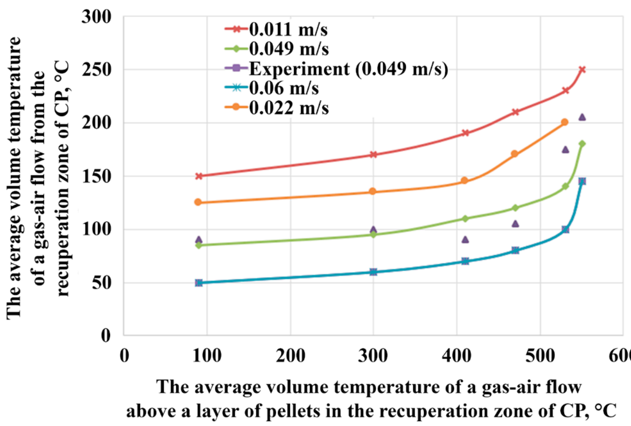
We study parameters of gas-air flows at the outlets from the zones of calcination and recuperation on the example of CP of OK-306 type, using the mathematical expressions (1)–(3). We calculate mathematically dependences of the average volume temperatures of gas-air flows $\theta_{gao}$ of temperatures of gas-air flows at the outlet from the zones of calcination and recuperation of CP.

We take into consideration the following in calculation of temperature of a gas flow $\theta_{gao}$, which appears at the outlet from a layer of pellets by formula (1): filtration of the gas-air flow through a layer of pellets $V_0$, which is 0.9 m/s; density ρ, which is 1.26 $kg/m^3$, a pressure difference $\Delta P$ of a gas-air flow at the inlet to a layer and after it, it is 3,040 Pa, and the coefficient β of volume expansion of gas, it is 0.003661 $K^{-1}$. Since the coefficient $K_L$ affects the temperature of a gas flow $\theta_{gai}$, which enters a layer, we calculate it by formula (2). It expresses the granulometric composition of a layer of pellets complexly by influencing shapes of particles of the furnace and sizes of pellets. We assume that the coefficient of a shape of furnace particles $k_f$ for a sphere is equal to 2/3, and the average diameter of furnace particles $d_{\text{cp}}$ is 4.6 mm. In calculations, we take the porosity of a layer of pellets as equal to 0.45 $m^3/m^3$ at a height of 0.45 m. We calculate the coefficient $\Psi_L$ of gas-dynamic resistance for a layer of iron ore pellets by formula (3), it is 11.76 if the Reynolds number is equal to 272.

Fig. 2, *a* shows determination of the average volume temperatures of gas-air flows $\theta_{gao}$ at the outlet from the calcination zone in the function of a change in temperatures of these flows, which exist above a layer of pellets in the zone of CP calcination in charts. As we know, a change in the speed of movement of CP calcination carts leads to fluctuations in temperature of a gas-air flow at the outlets of the investigated technological zones. Therefore, we perform calculations at the speeds of the movement of calcination carts: 0.06 m/s; 0.049 m/s; 0.022 m/s and 0.011 m/s at constant temperature of the gas-air flow supplied from the cooling zone technological temperature of 450 °C. We calculate similar characteristics for the recuperation zone of CP with the same data used in calculations for the calcination zone. Fig. 2, *b* shows characteristics for the recuperation zone.




*a*




*b*

Fig. 2. Changes in the average volume temperatures of gas-air flows $\theta_{gao}$, which come from a layer of pellets of technological zones: *a* – calcination; *b* — recuperation

The analysis of the characteristics presented in charts in Fig. 2 shows that the average volume of gas-air flows at the outlet from the zones of calcination and recuperation of CP depends significantly on the temperature of a gas air flow, which exists over a layer of pellets in these zones. So, for the calcination zone, this temperature changes almost linearly to the temperature of gas-air flows over a layer of pellets to 1,100 °C, and for the recuperation zone – 500 °C.

We performed experimental studies to check reliability of calculation characteristics of changes in temperatures of gas-air flows $\theta_{gai}$, which enter a layer of pellets of the CP zones of calcination and recuperation, and the output average volume temperatures $\theta_{gao}$ at the outlet from these zones obtained mathematically. We used an infrared thermometer of MS6550V model for temperature measurement of a gas-air flow. The temperature range of the thermometer is between minus 32 °C and 1,650 °C with a measurement error of ±1.5 %. We measured the speed of movement of calcination carts through CP zones using a contactless GEL 247 (Lenord Bauer) rotor speed sensor. The range of measurements of the speed of movement of calcination carts by this sensor is from 0 to 25 kHz.

Fig. 2, *b* presents the result of the experiment. We measured changes in the average volume temperatures of gas-air flows at the outlet from the technological zones of calcination and recuperation at the same values of the temperatures of gas-air flows, which were set mathematically at the inlets to these zones. We carried out the experiment at the speed of movement of calcination cars through the zones of CP of 0.049 m/s. The results of the calculation and the experiment presented in charts in Fig. 2, *b* show that the temperatures of gas-air flows at the outlet from the recuperation zone up to a value of 300 °C almost coincide at the speed of movement of calcination carts of 0.049 m/s. Further these characteristics differ, but by no more than 35 °C. The relative error of the channel of measurement of temperature of gas-air flows is 7 %, and of the measurement of the speed of calcination carts is 2.5 %.

The average volume temperatures of gas-air flows at the outlet from the technological zones of calcination and recuperation of CP depend also functionally on the rate of filtration of these flows through a layer of pellets on calcination carts. The rate of filtration of a gas flow depends on the height and porosity of a layer of pellets. It is necessary to maintain the optimal height of a layer on calcination carts in order to ensure the normalized thermal process for production of pellets. However, under production conditions, the height and porosity of a layer of pellets on calcination carts change from the zone to the zone due to drying of moisture, calcination of calcium, fluctuations of the granulometric composition, etc. Therefore, it is necessary to detect an effect of the height of a layer of pellets on the average volume temperature of a gas-air flow.

We took the following heights of a layer on calcination carts when performing calculations of the average volume temperature of gas-air flows: 450 mm, 350 mm, and 250 mm. At the same time, the porosity of a layer of pellets remained equal to 0.45 $m^3/m^3$. Fig. 3 presents the obtained characteristics in charts. They have the form of exponents with the same gas permeability of a layer. The higher is the height of a layer of pellets, the lower is the average volume temperature of a gas-air flow at the outlet from the technological zone of CP.

As presented in formula (1), the larger is the difference in pressure $\Delta P$ of gas-air flows at the inlet to a layer and after it, the higher is the average volume temperature of a gas-air flow $\theta_{gao}$, which comes from a layer of pellets. The average volume temperature decreases at the outlet from the calcination zone with an increase in the speed of passage of a gas-air flow through a layer of pellets. Charts in Fig. 3 confirm this. The charts take into consideration the difference in the pressure of the gas-air flow to before entrance to a layer of pellets on calcination carts and after leaving it.

We took following values 70 Pa, 60 Pa and 50 Pa as the values of the difference in pressure of gas-air flows for calculations of formulas (1)–(3). The pressure in gas-air chambers of the drying technological zone was 4,000 Pa. With an increase in the pressure difference of the gas-air flow speed, its temperature decreases at the outlet from the calcination zone according to the exponential law (Fig. 3).

Control of parameters of a gas-air flow by ACS system of smoke exhausters provides normalized distribution of pressure and temperature of gas-air flows over the technological zones of CP. ACS of smoke exhausters operates in the function of average volume temperatures of gas-air flows, which leave the technological zones of calcination and recuperation.

We used a general mathematical model to study redistribution of gas-air flow temperatures between CP technological zones. The basis of the model is separate mathematical models for each CP technological zone. We assumed that the output characteristics of the models for each subsequent zone are the outputs of the previous model of the technological zone. The equations (4) and (5) represent mathematical models of technological zones.

We took into consideration the following for these studies: the dynamic viscosity of a gas-air flow μ, it was $53.6 \cdot 10^{-6}$ Pa·s, the calculated coefficients $\alpha$ and $b$, which depend on a size and shape of pellets, they were 0.07 and 0.59, respectively. At control of gas-air flows over the zones of CP, the coefficients $k$ of heat consumed by heating of pellets were equal to 0.6 and 0.95, respectively, for zones of drying and preheating. Losses of a coolant for treatment of pellets in the calcination area $G_{coi}$ was 4.42 m$^3$/h. The estimated specific heat of pellets $C_o$ and gas-air flows $C_{sg}$ were 1.24 and 1.34 kg·K, respectively. The length $L$ of each of the zones of calcination and recuperation was 16 m, and of the cooling zone – 24 m by flows. The area $S$ of the plate of pellets, through which a gas-air flow was pumped out, was 144 m$^2$ for each zone of calcination and recuperation.

Fig. 4 presents estimated changes in parameters of gas-air flows (pressure and temperature) along the length of a calcination plant of OK-306 type. There are charts constructed using mathematical models of technological zones of calcination, recuperation and cooling at the control of gas-air flows at CP using the system of mathematical expressions given by the system of equations (4) and (5). Mathematical models of drying and preheating zones at control of gas-air flows over CP zones complement the system of mathematical expressions (4) by equations (5).

In calculations, we assumed the values of the pressure of the gas-air flow (Fig. 4, *a*) pumped by a smoke exhauster from the calcination zone to the zones of drying and preheating as equal to 500, 550 and 620 daPa. At the same time, the atmospheric air was pumped by a smoke exhauster into the technological cooling zone. The pressure of atmospheric air in gas-air chambers of the cooling zone was 730 daPa. This pressure varies from the cooling zone to the preheating zone of CP.

The values of the pressure of a gas-air flow are the highest in the zones of drying and calcination of pellets with the maximum value of the pressure of the gas flow generated by smoke exhausters (Fig. 4, *a*). Thus, we obtain the desired rate of filtration of a gas-air flow through a layer of pellets to ensure a level of intensity of conduction of heat exchange processes. Fig. 4, *b* shows charts 1–3, which reflect the functional dependences of changes in the temperature of gas-air flows over a layer of pellets along the length of CP. And charts 4–6 in this figure determine changes in the average volume temperature of gas-air flows at the outlet from a layer of pellets in the zones of calcination and recuperation. We obtained charts 1–3 and charts 4–6 by changing the pressure in the calcination zone to 5,000 Pa, 4,500 Pa and 4,000 Pa, respectively, at the constant speed of calcination carts of 0.049 m/s, the height of a layer of pellets of 450 mm and the porosity of a layer of pellets of 0.45 m$^3$/m$^3$.

The highest value of the temperature of flows was in the CP zones of calcination and recuperation. The temperature of the flows, which leave these technological zones, also depends on the values of these temperatures. The higher is the temperature of the gas-air flows in the zones of calcination and recuperation, the higher is the temperature of these flows at the outlet from these zones at the same height of a layer of pellets of 450 mm.

The obtained results indicate possibility of using the temperature of a gas-air flow at the outlet of the calcination and recuperation zones for control of the thermal process in production of pellets. That is, the temperature of gas-air flows at the outlets from the zones of calcination and recuperation is rationally used in the automated control system of smoke exhausters of CP.

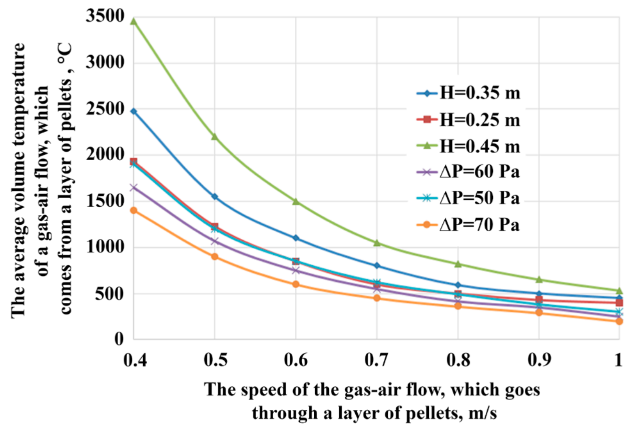
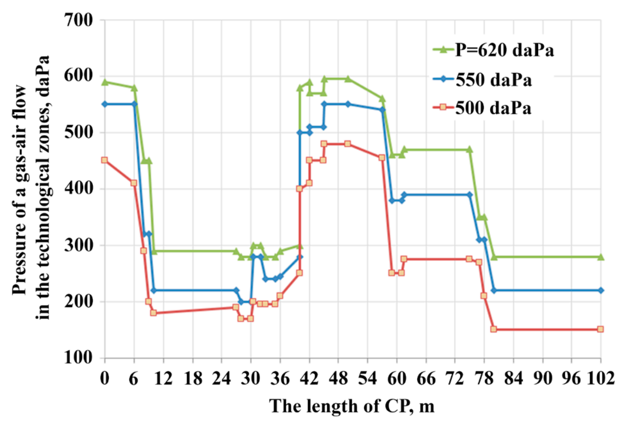



Fig. 3. Changes in the average volume temperatures of gas-air flows at the outlet from the calcination zone on the speed of movement of these flows, taking into consideration the height of a layer of pellets and the pressure difference at the inlet and outlet of a layer pellets

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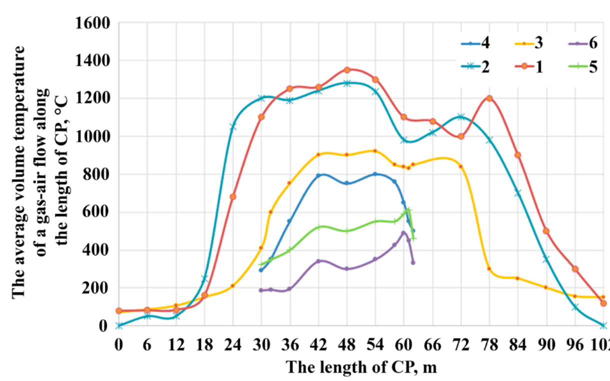


*b*

Fig. 4. Charts of calculations of parameters of gas-air flows in technological zones: *a* – pressure; *b* – average volume temperatures above a layer of pellets along the length of CP and at the outlet from a layer of pellets in the zones of calcination and recuperation

We also determined a change in the temperature of a gas-air flow at the boundary of "layer – bed" along the length of CP to check the adequacy of correctness of the calculations performed.

We carried out the experiment at a constant pressure of a gas flow of 4,500 Pa in the calcination zone, the speed of movement of calcination carts of 0.049 m/s, the height of a layer of pellets of 450 mm and the porosity of a layer of pellets of 0.45 $m^3/m^3$. The rate of filtration of gases through a layer was 1.2 $nm^3/s$ for the drying and cooling zones, and 0.6 $nm^3/s$ for the zones of preheating, calcination and recuperation. We used an infrared thermometer of MS6550B model to obtain experimental data of temperatures on the "layer-bed" boundary along the length of CP. To measure the height of a layer on calcination cart, we used the smart impulse radar laser sensor of DCRD1000A6 26 Ghz type, which has an output signal of 4–20 mA OrRS485 and Modbus/RTU protocol. We measured gas air flow pressure with the smart high-precision sensor of excess/absolute pressure of DMD 331-A-S-GX/AX.

Charts presented in Fig. 5 show the results of comparisons of correctness of the change in temperature at the "layer-bed" boundary along the length of CP of the calculated and experimental data. The relative error of measurement of temperature of a gas-air flow does not exceed 12 %. The accuracy of measurement of the height of a layer of pellets by this sensor was ±5 mm.

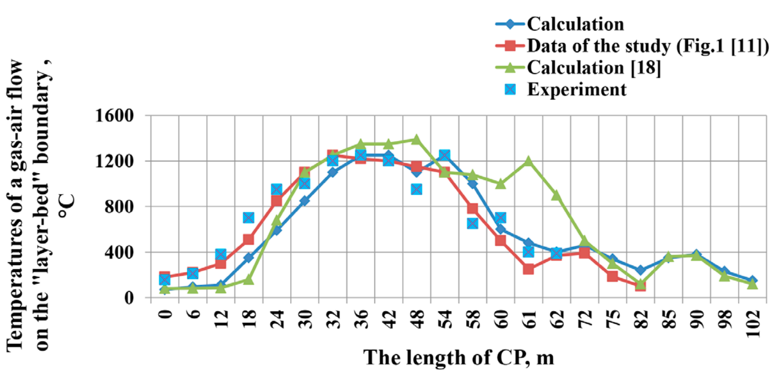


Fig. 5. Charts of comparisons of correctness of the calculations performed with similar calculations given in the scientific articles [11, 18] and experimental data

The results of calculations of the change in temperature of a gas-air flow at the "layer – bed" boundary along the length of CP showed that the blue chart is very close to the chart obtained by calculation given in [11] and does not differ significantly from the chart in [18]. Thus, we confirmed the adequacy of calculations experimentally.

## 6. Discussion of results of studying the process of redistribution of gas-air flows in the technological zones of CP

An analysis of the charts shown in Fig. 2, *a* and the change in the average volume temperature of a gas-air flow, which comes from a layer of pellets $\theta_{gao}$ at the outlet from the calcination zone of CP, depends on the temperature of 1,100 °C of the gas stream over a layer of pellets in the calcination zone almost linearly. However, the gas flow changes rapidly to a temperature of 1,250 °C by exponential law after the temperature of 1,100 °C. The speed of movement of calcination carts above 0.06 m/s leads to a decrease in the average volume temperature of a gas-air flow at the outlet from the zone of calcination of pellets, it decreases almost to 200 °C. This indicates that a layer of pellets on calcination carts does not have time to warm up and does not reach the required value in lower layers of pellets.

A change in the average volume temperature of the gas-air flow at the outlet from the recuperation zone of CP depends on this flow above a layer of pellets along the length of CP almost linearly. Charts presented in Fig. 2, *b* confirm this.

An increase in the speed of movement of calcination carts from 0.011 m/s to 0.06 m/s leads to a decrease in the average volume temperature of the heated gas-air flow in 1.7 times. This flow comes from the recuperation zone of CP at the regulated maximum temperature in the gas-air chamber of 550 °C.

An increase in the height of a layer of pellets on calcination carts by 30 percent (Fig. 3) at the constant gas permeability of this layer leads to a decrease in the average volume temperature of the gas air flow at the outlet from the calcination zone of CP by 2.5 times by the exponential law. The speed of the gas-air flow through a layer of pellets was 0.049 m/s. Therefore, it is necessary to maintain optimally the height of a layer of 450 mm, which is regulated at CP of OK-306 type. The difference in pressure of a gas-air flow between the inlet and outlet from a layer depends on the height of a layer of pellets on calcination carts. As we can see in Fig. 3, the dependence is exponential. The speed of movement of this flow through a layer of pellets determines the dependence. The lower is the speed of a gas-air flow, the higher is the temperature of such a flow at the outlet from the calcination zone of CP.

The performed study allows us to draw the following conclusion. An increase in the height of a layer of pellets at CP calcination carts leads to a proportional decrease in the average volume temperature of a gas flow at the outlet from the calcination zone. Moreover, the comparison of the heights of a pellets layer indicates the depth of the thermal processes. This means that taking into consideration of this fact opens the possibility for effective regulation of properties of a gas-air flow directly by smoke exhausters of CP under conditions of an enterprise. The temperature at the outlet from the calcination zone of pellets changes by up to 30 percent at a change in a pressure difference of speeds of gas-air flows from 340 Pa to 250 Pa (Fig. 3). This means that taking into consideration of this fact opens up the opportunity for efficient control of the thermal process of pellets production at CP. We should note that we performed comparative calculations at changes of gas-air flows pressures from 500 daPa to 620 daPa with smoke exhausters and at supply of this flow to the drying and preheating zones. Here pressures of gas-air flows are distributed over the technological zones of CP almost proportionally. Calculations presented in charts in Fig. 4, *a* confirm this. A change in the pressure of this flow, pumped by a smoke exhauster, of 120 daPa changes the flow pressure throughout the length of CP by 1.4 times.

In addition to studies on redistribution of pressures of gas-air flows in the technological zones, we also studied redistribution of the temperatures of these flows over these zones of CP. In the course of the studies, we took into consideration that ACS of smoke exhauster from the technological zones of calcination and recuperation. Fig. 4, *b* shows calculation changes in the temperatures of gas-air flows along the length of a calcination plant of OK-306 type. We accepted the following values of pressures of the gas-air flows generated the smoke exhausters from the calcination zone in the gas-air drying chamber: 620, 550 and 500 daPa. And the dilution of previous heating in the gas-air chamber was 4,000, 3,500 and 3,000 Pa.

It is evident from Fig. 4, *b* that the excess in the temperature of the gas-air flow over a layer of pellets affects the average volume temperature at the outlet of it significantly. The average volume temperature of the gas-air flow at the outlet from a layer of pellets in the zones of calcination and recuperation can reach a reduction of up to three times of the value at a change in pressure in the calcination zone from 5,000 Pa to 4,000 Pa, the constant speed of calcination carts of 0.049 m/s, the height of a layer of pellets of 450 mm and the porosity of a layer of pellets of 0.45 $m^3/m^3$.

The supply of a gas air flow intended for drying of pellets on the calcination carts occurs by blowing from the zones of calcination and recuperation of CP by smoke exhausters through gas-air chambers. There is the temperature of a gas-air flow from 50 °C to 180 °C (Fig. 4, *b*). Maintained in the drying zone 1 (Fig. 1). At the same time, these temperatures range from 210 °C to 400 °C for drying zone 2. There is a discharge of 2,200 Pa generated in the drying zone (Fig. 4, *a*).

The study of the modeling results shows that the temperature of gas-air flows, which come from the high-temperature zones, can vary greatly. The ratio of the amount of cold air and burned natural fuel maintains the given value of temperatures. For this purpose, a smoke exhauster pumps the atmospheric air, it is heated in cooling zones 6 and 7. The heated air from cooling zone 6 goes into the calcination and recuperation zone of CP. Therefore, the temperature of gas-air flows in these zones, as we can see in Fig. 4, *b*, changes substantially. The gas-air flow from the cooling zone 6 goes directly by the flow to drying zone 2. It is desirable to maintain its temperature, which enters a layer of pellets, at a temperature of 350 °C (Fig. 4, *b*). It is possible to achieve due to atmospheric air supplied from the cooling zone 7, where atmospheric air is pumped by a smoke exhauster of 650 daPa. If the temperatures of gas-air flows at the outlet of the CP technological calcination zone are not sufficient, then it is necessary to add heat from combustion of natural fuel in burners installed in this zone. In this case, the atmospheric air from cooling zone 6 in the ratio of "gas-air" is fed to burners of calcination.

There is discharge maintained automatically at the level of 50–90 Pa by the flow of air supplied by a smoke exhauster to cooling zone 7 in the calcination zone. The processes, which occur in the preheating zone, and especially in the calcination zone, cause temperature stabilization in the furnace. This ensures that we get strong pellets. Stabilization of the heating process of a layer of pellets, when it accumulates a constant specific heat, contributes to its more stable utilization in other zones, which leads to a general increase in the rate of efficiency of the thermal process.

The analysis of the obtained results indicates that we have to know parameters of temperature of gas-air flows at the outlet from the zones of calcination and recuperation and to control pressure of these flows and to feed them into the technological drying and preheating zones in order to control the thermal process in production of pellets. It is necessary to control pressure control of a gas flow by smoke exhausters using a special algorithm, while controlling the supply of atmospheric air to the technological zones of calcination and recuperation through the cooling zones of CP. We should use operative evaluation of parameters of a gas-air flow and adaptive predictive control of the processes of thermal treatment of pellets. Therefore, it is rational to use the average volume temperature of gas-air flows, which come from the zones of calcination and recuperation, in the automated control system of smoke exhausters of CP.

Computer modeling gave us a possibility to investigate the influence of average volume temperatures of a gas-air flow from the calcination and recuperation zones on the thermal process of producing of iron ore pellets. The obtained modeling results give possibility to predict temperature changes in different technological zones of CP. The model makes possible studies on the process of distribution of a gas-air flow between all technological zones.

The obtained study results (Fig. 5) do not differ from the practical data from well-known works [4, 6, 19], which also associate a change in duration of the thermal process in the production of pellets with an influence of gas-air flow parameters in this process. But, unlike the results of studies published in these works, we can confirm the data on the influence of temperature, pressure and speed of a gas air flow on the process of the thermal process in production of pellets as follows:

– the main regulator of the thermal process in production of pellets at CP is redistribution of high-temperature gas-air flow from the technological zones of calcination and recuperation between the zones of drying, preheating and cooling, which makes possible to save energy;

– rational use of air in the cooling zone at the automatic management of a smoke exhauster and redistribution of flows heated in these zones to technological zones of calcination and recuperation;

– correct choice of parameters of the height of a layer of pellets on calcination carts, pressure difference at the inlet and outlet of a layer of pellets, temperature, pressure and speed of a gas-air flow at the outlet of the technological zones of calcination and recuperation, and also air pressure pumped by a smoke exhauster to the zones of calcination and recuperation through the cooling zone has a significant influence on the thermal process of pellets production at CP.

We can consider such conclusions as expedient from a practical point of view, as they make it possible to approach determination of the required thermal process of calcination of pellets at CP reasonably. From a theoretical point of view, the results of the performed studies give us possibility to assert the definition of the mechanism of control of the thermal process of pellets production. A certain advantage of this study is that the automated system uses parameters of a gas-air flow that goes from the technological zones of calcination and recuperation of CP.

The study has made it possible to develop and introduce an automated control system for management of smoke exhausters at average volume temperatures of gas-air flows at the outlet from technological zones of calcination and recuperation. We can use it under industrial conditions. Operation of such a system improves the thermal process and gas-dynamic operation of the CP technological zones.

However, it is impossible not to notice that the results of the study indicate an ambiguous effect of parameters of an output gas-air flow on a change in the mechanical strength of pellets. Such uncertainty imposes certain limitations on the use of the results that can be interpreted as disadvantages of this study. Failure to remove these limitations within the framework of this study generates a potentially interesting direction for further research. In particular, we can aim them at detection of the influence of physical and chemical properties in real time on parameters of a gas-air flow and the course of the thermal process in production of pellets. The disadvantage of the study is that we used technical parameters of only one CP type - OK-306, which is insufficient and incomplete.

The obtained results are useful for changes of the unevenness of conditions of the heat treatment of pellets by improvement of the uniformity of redistribution of gas-air flows over the technological zones of CP due to optimization of the supply of gas-air blow.

There were no studies on determination of parameters of a gas-air flow at the outlet of technological zones of calcination and recuperation and the influence of this flow on other zones of CP before.

Further improvement of this study is possible in the direction of control of the thermal process of pellets production at CP, taking into consideration the influence of the physical-and-chemical composition of pellets on parameters of a gas-air flow.

## 7. Conclusions

1. The conducted studies revealed peculiarities of the technological process of calcination of pellets. They consist in necessity for control of smoke exhausters by parameters of average volume temperatures of gas-air flows, which are output flows from the zones of calcination and recuperation of pellets. Therefore, we can state that the analytical dependencies used and the developed structural scheme of automated control of smoke exhausters of CP take into consideration temperatures of gas-air flows. For operational control, it is better to evaluate parameters of temperature of gas-air flows, which go out from the zones of calcination and recuperation of CP. This makes possible to control gas-air flows in the zones of CP, providing a normalized thermal process for production of pellets.

We established that temperatures of gas-air flows depend on the height of a layer of pellets on calcination carts, the difference in pressure at the inlet and outlet from a layer of pellets and the speed of passing of this flow through a layer of pellets.

We can maintain the given value of their temperatures by the change of atmospheric air under the control of a smoke exhauster, which pumps it into the cooling zone of CP. As a result, we improve the thermal and gas dynamic operation of the technological zones of calcination and recuperation of CP.

2. We determined redistribution of temperature of gas-air flows in the technological zones of CP at the control of smoke exhausters in the functions of average volume temperatures of gas-air flows, which go out from the technological zones of calcination and recuperation. We used the mathematical model for the study. The model included an equation for determination of the temperature, pressure and speed of gas-air flows in the technological zones of CP. The basis of the mathematical model took into consideration that the inputs and outputs of the technological zones of CP are connected by equations of gas dynamics, heat transfer and mass transfer. We assumed that the output characteristics of pellets for each subsequent zone are the outputs of the previous zone of CP in the study of distribution of temperatures of gas-air flows in the technological zones of the CP.

Using the results of computer modeling for determination of the influence of parameters of gas-air flows from the technological zones of calcination and recuperation on the thermal process of production of iron ore pellets, it is possible to predict changes in parameters of the thermal process in other zones of CP. The model gives possibility to investigate the process of distribution of gas-air flows between zones of drying, preheating, burning and cooling. We found actions for control of smoke exhausters based on the mathematical model. This, in theory, will lead to a decrease in the amount of required energy resources. The results of the study will make it possible the implementation of a mathematical model in the automated control system of smoke exhausters. It is possible to apply the developed system under industrial conditions.

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