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IMPROVING ENERGY EFFICIENCY OF COAL TRANSPORTATION BY ADJUSTING THE SPEEDS OF A COMBINE AND A MINE FACE CONVEYOR

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Об'єктом дослідження є процес формування середньозважених питомих енерговитрат на транспортування гірничої маси лавним скребковим конвеєром при інтенсивному вуглевидобутку в умовах нерівномірності руху очисного комбайна. Предмет дослідження – закономірності впливу нерівномірності швидкості подачі очисного комбайна на енергетичні показники транспортування скребковим конвеєром очисного забою в умовах інтенсивного вуглевидобутку. Метою роботи є обґрунтування способу підвищення енергоефективності функціонування системи «очисний комбайн – забійний конвеєр» в умовах інтенсивної вуглевидобутку. Виконано статистичну обробку результатів експериментальних досліджень швидкості подачі очисного комбайна КДК500 в умовах 23 східної лави пласта c_{11} шахти «Південнодонбаська» (м. Вугледар, Україна) ДП «Донецьквугілля», здійснених інститутом «Донгіпровуглемаш» (Україна). Розроблено структурну і математичну моделі процесу виникнення вихідного вантажопотоку з очисного вибою і формування питомих енерговитрат на транспортування гірської маси скребковим конвеєром лави. Математична модель робочого процесу ураховує вплив величини і нерівномірності швидкості подачі очисного комбайна на енергоспоживання при транспортуванні вантажу. Встановлено суттєву нерівномірність швидкісних режимів, продуктивності очисного комбайна, що викликано гірничо-геологічними умовами й характером технологічного процесу, існуючими методиками узгодження режимів роботи видобувного і транспортного обладнання очисних вибоїв. Встановлено вплив швидкісних режимів та продуктивності комбайна на питомі енерговитрати на транспортування вантажу скребковим конвеєром лави.

Наслідком є висока нерівномірність вантажопотоку як в лаві, так і на подальшому транспортному ланцюжку, що викликає істотне підвищення енерговитрат на транспортування вантажу. Досліджено вплив швидкісних режимів роботи комбайна, як наслідок – його продуктивності, на енергетичні показники процесу транспортування вугілля та на характер розподілення вантажопотоку. Встановлено: підвищення швидкості подачі очисного комбайна і зниження швидкості скребкового конвеєра знижує питомі енерговитрати на транспортування відбитої гірської маси у лаві

Ключові слова: вугільні комбайни, питомі енерговитрати, вибійні скребкові конвеєри, характеристика вантажопотоку, напрямок руху комбайна

1. Introduction

Effective functioning of such an energy-intensive industrial complex as a modern coal enterprise with intensive mining is associated with the implementation of energy-efficient technologies, as well as the optimization of the structure and operating modes of technological equipment. One of the conditions for such optimization is the operation of technological equipment at the lowest possible energy cost while ensuring the required performance of the enterprise's structural units [1].

Transportation equipment at mining enterprises is an important part of the technological process, as well as its continuation. Transportation means that operate in the mines at enterprises of intensive coal mining imply the use of belt conveyors as the primary vehicle in capital workings at the level of a mine shaft yard. One of the advantages of a belt conveyor is high efficiency when transporting a bulk cargo in continuous flow. However, this class of transportation machines has certain shortcomings, one of which is the high cost of cargo transportation. Specific expenditures for the transportation of cargo by belt conveyors per cost of 1 ton of mined coal are about 20 % [2].

As shown by the theoretical and experimental research [3], high energy costs for the displacement of cargo by a belt conveyor are related to the high non-uniformity in an input cargo flow that generates the load on a conveyor, which differs from the maximum possible. As a result, energy consumption during cargo transportation is significantly affected by idling [4]. For mine face scraper conveyors, this problem is compounded by the mobility of rock mass loading front, as a result of which a belt conveyor over the most part of machine time turns out to be underutilized, not only in terms of the receiving capacity of a carrying body but lengthwise as well.

An actual loading of the mine face conveyor and the output cargo flow from a breakage face can be established over time only based on a change in the performance and location of a cleaning combine under representative mining conditions. Therefore, to adequately assess energy consumption at a mine face conveyor, it is necessary to undertake an experimental research into productivity (or feed speed) of a cleaning combine at an enterprise of intensive coal mining.

Therefore, it is a relevant task to reduce the cost of cargo transportation, to assess an impact of the magnitude and non-uniformity in a cleaning combine's feed speed on energy consumption during cargo transportation by using the results from experimental studies under industrial conditions.

2. Literature review and problem statement

The experience of energy saving practices at the mine face scraper conveyers under conditions of unevenness of the input cargo flow demonstrates a widespread implementation of progressive technologies ensuring a reduction in the cost of coal produced at mining enterprises. Traditionally, the reason for high energy consumption by the mine face scraper conveyors is considered to be the large resistance forces to the motion of a scraper chain. This relates to the friction between the chain, a cargo, and a pan line, deformation, cargo agitation and regrinding [5] when dragging it. However, insufficient attention has been given to the non-uniformity in a cleaning combine's displacement speed and, consequently, to the underloading of a mine face scraper conveyor and a mismatch between capacities of a cleaning combine and the coal face conveyor [6].

Study [7] has shown that indicators for energy use at mines are due to the following factors: mining-geological, mining-technical, technological, and organizational. The first ones include depositing conditions and the geological structure of a coal seam, water- and methane abundance. The second ones imply the frequency of activities for maintenance and repair, the placement of equipment, elimination of obsolete equipment, the application of advanced transportation vehicle drives. The third factors include the mutual arrangement of workings and work sites, the system of development, ventilation equipment, water drainage, transportation, lifting, etc. Organizational factors are the energy management, personnel policy, accounting of coal, etc.

The specified paper has confirmed experimentally under representative conditions: the optimization in line with these criteria can ensure the reduction of energy consumption at coal enterprises by 26–55 %. However, there is no evaluation of the effectiveness of harmonizing the operational modes of a cleaning combine and a mine face scraper conveyor.

The operation of a mine scraper conveyor has a significant impact on energy consumption indicators at a mine. The authors of [8], based on the results of modeling, derived a quadratic dependence for the performance of a scraper conveyor on the coefficient of cargo friction against a pan line. Due to the redistribution of cargo motion speeds at various points of the flow's cross-section, the best performance was demonstrated by a coal face scraper conveyor when the static coefficient of cargo friction reached 0.4. That points to the need to optimize the structure and operating modes of a scraper conveyor based on its energy consumption criterion while improving its technological level. However, there is no assessment for the impact of the input cargo flow's non-uniformity and the mine face conveyor's underload on energy costs during cargo transportation.

Study [9] applied a mechatronic approach to analyze moving mining complexes of technological equipment; the authors established the nature of relationship, as well as mutual influence, between the individual components of the complex as a mechatronic system. However, insufficient attention has been paid to the issue on the non-uniformity of displacement of extraction equipment at a mining complex and its impact on technical and economic performance indicators for individual links in the technological process at a mining enterprise.

Paper [10] gives requirements to developing a simulation model of work of a cleaning combine at a mining complex, making it possible to select the optimal operating mode of the latter based on geological and mining-technical conditions. However, not enough attention was paid to the issue on changing the conditions for functioning of the complex, which could significantly affect the results of optimal choice of technological equipment.

Works [11, 12] considered specific ways to reduce energy consumption by a mine scraper conveyor – the application of new electrical materials for a motor part of the drive, as well as a controlled drive at a conveyor. However, not enough attention has been paid to the impact of the technological component of the process of coal (rock) array destruction on energy parameters of the conveyor.

Papers [13, 14] note the uneven character of cargo flow from coal face and make it possible to perform its modeling as a random process. However, no attention is paid to the reasons for the non-uniformity of a mine cargo flow and the reception of cargo by a transportation chain of the mine. That is, there is a need to analyze the mining-geological, mining technical, technological, and organizational factors occurring in the operation of mining and tunnel sites at mining enterprises.

Study [15] outlines the concept of the adaptation of mine face scraper conveyors to the conditions of their operation. However, there is no elucidation for the issue on a random nature of displacement speed of the combine, and, consequently, the input cargo flow at mine face conveyor.

The relevance of the issue on reducing power consumption during cargo transportation, in particular by adapting the speed of vehicles moving to the sources of cargo flows, is confirmed by the results from numerous studies into a given issue, specifically [16], in relation to the belt conveyors. However, the specified work emphasizes the issue on improving the quality of electric power and fails to address the issue on the input cargo flow's non-uniformity influence on the energy consumption indicators for cargo transportation.

The energy model of a belt conveyor, described in [17], comes down to determining four estimation coefficients for its operating process. To illustrate the results of modeling, the authors selected a typical structure of the conveyor belt, for which they offered six kinds of optimization problems, the most characteristic of this class of transportation vehicles. However, there is no solution to the issue related to the influence of the input cargo flow's non-uniformity on the magnitude of energy consumption by a conveyor.

Thus, up to now, not enough attention has been paid to factors that determine the magnitude and unevenness of a mine cargo flow from a breakage face, as well as the energy consumption by mine face scraper conveyors during their operation, primarily the non-uniformity in feed speed of cleaning mechanisms at mining complexes. Therefore, it is necessary to undertake a further research to substantiate a technique to reduce energy consumption by the mine face scraper conveyor.

3. The aim and objectives of the study

The aim of this study is to substantiate a technique to improve energy efficiency in the operation of the system "a cleaning combine – a mine face conveyor" under conditions of intensive coal mining, based on the results from experiment that are characteristic of combine coal faces.

To accomplish the aim, the following tasks have been set:

– to determine experimentally the magnitude and nature of change in the displacement speed of a cleaning combine, as well as the energy intensity of a coal destruction process during operation of extraction equipment under representative conditions;

– to construct, based on the results from experimental study, the structural and mathematical model of the process that forms the output cargo flow and the weighted specific energy costs for transporting coal by a scraper conveyor at the breakage face;

– to propose, employing the results from a computational experiment that involves the built mathematical model, a technique to improve energy efficiency of the system "a cleaning combine – a mine face conveyor" under conditions of intensive coal mining.

4. Materials and methods of experimental research

An experimental study has been carried out; its design and conditions are set out below. An extracting machine used was the combine KDK500. Acceptance testing was performed by the Institute "Dongiprouglemash" (Ukraine). At the first stage, in order to define limiting characteristics, the testing of the feed mechanisms was carried out at the bench by the plant manufacturer. A study into operation parameters at the second stage was performed along a coal face of seam c_{11} (a seam thickness is 1.55–1.75 m, angle of incidence is 6–8°, coal of grade DG). Applicability of the combine KDK500 in terms of the minimum seam capacity with the roof type used in a mine was determined by taking into consideration the measurement of actual excavated capacity of the seam. We measured seam capacity every 10 m lengthwise the breakage face. The rated capture width is determined by measuring the actual size between a new and an old mine face. Measurements were performed every 10 m lengthwise the mine face.

The experiment's design is as follows. Coal face is divided into measures sections of length x_r, $\Sigma x_r = L$, where L is the breakage face length. Time t_r required to travel over each measured section is measured by a stopwatch. The actual feed speed, v_n, m/min, is derived from formula:

$$v_{nr}=x_r/t_r. \qquad (1)$$

Under experimental conditions, the combine feed speed is characterized by high non-uniformity, as will be discussed below. The reason for a change in the combine feed speed is a variable strength of the starting coal array along the length of breakage face, as well as the pack of roof rocks, captured by the combine's controlling element at coal extraction.

We calculate the combine's performance along measured section r

$$Q_{\text{comb}.r}=60HB\rho' v_{pr}, \text{ t/h}, \qquad (2)$$

where H is the seam thickness, m; B is the width of a combine grip, m; ρ' is the volumetric density of a cargo material, t/m^3.

We calculate the maximum performance of a mine face scraper conveyor

$$Q_{\text{conv}}=3600bh\rho v, \qquad (4)$$

where b is the width of a scraper conveyor's pan line, m; h is the height of a scraper conveyor's pan line, m; ρ is the bulk density of broken rock mass, t/m^3; v is cargo speed transportation, m/s.

The experimental study has shown that the combine feed speed is random in character, it is characterized by the high non-uniformity (a coefficient of variation is 0.5), and it ranges from 1.2 m/min. to 7.5 m/min. Performance of a combine, linearly dependent on feed speed, is also a random variable. Estimation of specific energy consumption for coal destruction is on average 0.95 kWh/t. The results of experimental study into combine's performance are shown in Fig. 1.

It follows from an analysis of Fig. 1 that the combine's performance varies depending on its location along a coal face. Based on statistical processing of the experimental results, a mathematical expectation for the combine's performance (when it is indexed for the length of a coal face) is 290 t/h (ranges from 100 to 570 t/h), and its coefficient of variation is 0.5.

Thus, the experimentally established, under representative conditions, feed speed and performance of the combine have high non-uniformity (coefficient of variation is 0.5), which significantly affects the uneven cargo flow output from coal face. The obtained performance characteristics for a cleaning combine are characteristic of combine coal faces.

When cutting a strip of coal along a coal face, most of the time the performance of a scraper conveyor does not match the performance of a cleaning combine. The latter utilizes the scraper conveyor performance reserves by 43 %, which is not a rational techno-economic indicator for the operation of cleaning equipment and indicates the need to adjust the operating mode of the conveyor.

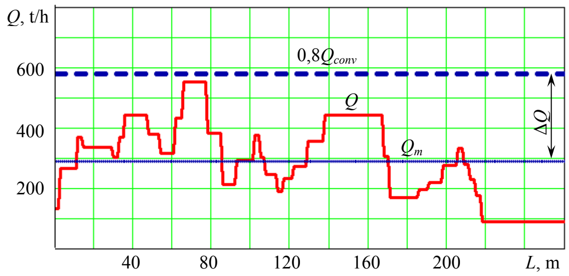


Fig. 1. Change in performance of the combine KDK500 (Q) depending on length of a lava (L) at direct motion, its mean (Q_m) and maximum performance value in terms of the receiving capacity of a mine face conveyor ($0,8Q_{conv}$), as well as the conveyor performance reserve (ΔQ), based on the results from experimental study performed at the Institute "Dongiprouglemash"

The source data to determine and further adjust the operational mode of the mine face conveyor:

– the type of a combine and the technological scheme of coal extraction;

– the length of a coal face, L, m;

– the length of measured sections, x_r, m; $\Sigma x_r = L$;

– feed speeds and theoretical performance of the combine along measured sections, v_{pr}, m/min., Q_r, t/min.;

– the time required to travel over measured sections, t_r, min.

Thus, the experimental study of the magnitude and non-uniformity of feed speed of a cleaning combine and the energy intensity of a coal destruction process has yielded the following results. Mathematical expectation of the cleaning combine performance is 290 t/h (ranges from 100 to 570 t/h), and its coefficient of variation is 0.5, predetermined by the uneven feed speed of the combine (a range of 1.2–7.5 m/min). The feed speeds and performance of the cleaning combine do not match the speed of the chain and performance of the scraper conveyor – conveyor's capacity is used by 43 %. The experimental study into performance of the cleaning combine has been performed under representative conditions of the coal mine and characterizes combine coal faces.

5. Results of theoretical research

5. 1. Devising the structure of the process that forms specific energy consumption for the transportation and for the output cargo flow

The structure of the process that forms the weighted specific energy consumption and the output cargo flow was developed taking into consideration the magnitude and non-uniformity of displacement speed of the cleaning combine. The time required to cut a strip of coal by a cleaning combine Σt_r was split into elementary segments, that is, we introduced a time-dependent sampling step Δt, s. At the same time, the number of registered intervals was $N=[\Sigma t_r/(\Delta t)]$, current time of registration – $t_i = i \cdot \Delta t$, $i \in [0; N]$, the combine's feed speed at time t_i, v_{pi}, m/min. corresponded to that observed when travelling over respective measured sections.

The structural model for the formation of an output cargo flow and the weighted specific energy costs for the transportation of coal at a mine face, taking into consideration the uneven cargo delivery to the conveyor and the mobility of a loading front, is shown in Fig. 2.

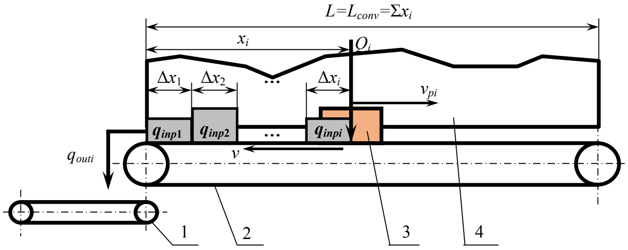


Fig. 2. Structural model for the formation of an output cargo flow q_{out} and the weighted specific energy costs W for coal transportation at the chain constant speed v at variable feed speed of the combine v_p: 1 — loader; 2 — mine face conveyor; 3 — cleaning combine; 4 — cut strip of coal

Fig. 2 shows that over time Δt_i a cleaning combine travels at feed speed v_{pi} over distance Δx_i along the route of the mine face scraper conveyor. Performance Q_i of the combine in this case is due to input cargo flow $q_{\text{inp}i}$. Therefore, at time t_i the combine travels a distance from the coal face's bottom window $x_i = \Sigma \Delta x_i$, and the output cargo flow $q_{\text{out}i} = q_{\text{inp}i - xi/v}$, where v is the velocity of the mine face conveyor. The total input cargo flow, located at a section of the conveyor route x_i, forms the loading of a scraper conveyor that influences specific energy consumption for the transportation of broken rock mass along a coal face. The structural model of the process that forms the output cargo flow and specific energy costs for coal transportation takes into consideration the effect exerted on these parameters by the magnitude and character of change in the cleaning combine's feed speed, as well as the speed of the conveyor's chain.

5. 2. Development of a mathematical model of the process that forms the weighted specific energy costs for the transportation of broken coal

Taking into consideration the built structural model of the process that forms the output cargo flow from coal face and the weighted specific energy costs for coal transportation at a mine face, we construct a mathematical model of the above-specified processes. The basis for the developed mathematical model is the formulae and dependences that are used in the technological estimation of the cleaning combine and the scraper conveyor.

Performance of the cleaning combine at time t_i:

$$Q_i = 60 H B \rho / v_{\text{p}i}, \text{ t/h}. \quad (5)$$

Displacement of the combine over the i-th interval of registration:

$$\Delta x_i = v_{\text{p}i} \cdot \Delta t / 60. \quad (6)$$

Position of the combine relative to the bottom window of a coal face (a place where rock mass is loaded onto a transportation chain) at time t_i:

– forward movement of the combine:

$$x_i = \sum_{i=0}^{i} \Delta x_i; \tag{7}$$

– backward movement of the combine:

$$x_i = L - \sum_{i=0}^{i} \Delta x_i. \tag{8}$$

Input cargo flow over the *i*-th interval of registration

$$q_i = \frac{Q_i}{3600} \frac{60 v_i}{60 v_i \pm v_{pi}} \text{ t/s}, \tag{9}$$

where v_i is the conveyor's chain speed at time t_i, m/s.

Note. A “+” sign corresponds to the forward motion, a “–” sign – backward motion of the cleaning combine.

The mass of coal, loaded onto a conveyor, at time t_i:

$$\Delta m_i = q_i \cdot \Delta t \cdot v v_i^{-1}. \tag{10}$$

The time required for the batch of cargo Δm_i to travel from a loading place to the place of unloading

– forward motion of the combine:

$$t_i^{/} = \begin{cases} 0, & i = 0, \\ x_i \left[i^{-1} \sum_{i=1}^{i} v_i \right]^{-1}, & \text{otherwise}, \end{cases} \text{ s}; \tag{11}$$

– backward motion of the combine:

$$t_i^{/} = \begin{cases} x_i \left[i^{-1} \sum_{i=1}^{i} v_i \right]^{-1}, & i < N, \\ 0, & \text{otherwise}. \end{cases} \tag{12}$$

The number of batches of cargo at a conveyor at the *i*-th moment:

– forward motion of the combine:

$$n_i = \left[\frac{t_i}{\Delta t} \right]; \tag{13}$$

– backward motion of the combine:

$$n_i = \begin{cases} i, & i \le t_i, \\ \left[\frac{t_i}{\Delta t} \right] & \text{otherwise}. \end{cases} \tag{14}$$

Conveyor loading:

– forward motion of the combine:

$$m_i = \sum_{i=i-n_i}^{i} \Delta m_i; \tag{15}$$

– backward motion of the combine:

$$m_i = \sum_{i=i}^{i+n_i} \Delta m_i. \tag{16}$$

The mean equivalent cargo mass per unit of length at a conveyor

$$q_{m.i} = \frac{m_i}{L}. \tag{17}$$

Specific energy costs for cargo transportation of cargo at moment t_i

$$W_i = \frac{(F_0 + k_m q_{mi}) v_i}{q_i L \eta_i}, \tag{18}$$

where F_0 is the circular traction effort of conveyor idling; k_m is the increment in the circular traction effort when increasing the workload on a conveyor by 1 t; q_i is the cargo flow from a coal face; η_i is the efficiency coefficient of the operating mode of a scraper conveyor at moment t_i.

According to [18–20], we statistically process the input cargo flow q_i and the mean conveyor loading per unit of length $q_{cp.i}$, we obtain:

$q_{cp.k}$, η_k, v_k is the mean loading per unit of length of the conveyor of class k and the respective efficiency coefficient for a scraper conveyor taking into consideration its mode of operation and the speed of transportation, determined by the conveyor control algorithm;

p_k is the probability of occurrence of the k-th class of conveyor loading per unit of length.

The weighted specific energy costs for cargo transportation

$$W_m = \frac{T}{m_\Sigma L} \sum_{k=1}^{n} \frac{(F_0 + k_m q_{mk}) v_k p_k}{\eta_k}, \tag{19}$$

where T is the duration of conveyor operation; m_Σ is the total weight of the cargo delivered by a conveyor over time T; n is the number of classes of loading at the conveyor pan line, according to the results from statistical processing of results of the experiment; η_k is the efficiency coefficient of the scraper conveyor operating mode that matches speed v_k and loading $q_{cp.k}$.

The circular traction effort of the idle conveyor and an increment in the circular traction effort while increasing loading by 1 ton are determined, respectively, from formulae

$$F_0 = 2 k_s g L q_0 \omega_0^{/} \cdot \cos\beta, \tag{20}$$

$$k_m = k_s g L \omega^{/} (\cos\beta \pm \sin\beta), \tag{21}$$

k_s is the coefficient of local resistances; q_0 is the chain's mass per unit of length; $\omega^{/}$, $\omega_0^{/}$ are the coefficients of resistance to the cargo and chain motion; β is the mean angle for setting a conveyor.

The total mass of the cargo delivered by a conveyor over time T

$$m_\Sigma = \sum_{i=0}^{N} q_i. \tag{22}$$

The efficiency coefficient of a scraper conveyor's operating mode is determined as follows:

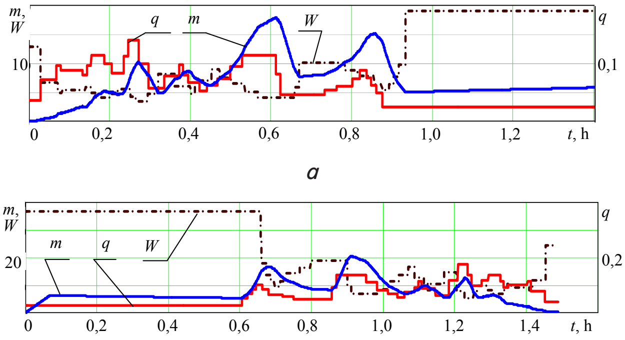
$$\eta_i = \eta_{n.i} \eta_{\text{reg}.i} \eta_{\text{dr}.i} \eta_{\text{m}.i} \eta_{\text{l}.i}, \tag{23}$$

$$\eta_k = \eta_{n.k} \eta_{\text{reg}.k} \eta_{\text{dr}.k} \eta_{\text{m}.k} \eta_{\text{l}.k}, \tag{24}$$

where η_n is the efficiency coefficient of electric network; η_{reg} is the efficiency coefficient of the regulator for a drive loading and the speed of a mine face conveyor; η_{dr} is the efficiency coefficient of the transmission part of a conveyor's drive; η_m is the efficiency coefficient of the mechanical part of the network's drive (reducer, couplings, drum); η_l is the coefficient efficiency of the mechanical part of a conveyor based on the loading mode [20] of its linear part.

Thus, formulae (5) to (24) are used in the mathematical model of the process that forms the weighted specific energy costs for the transportation of broken coal by a mine face scraper conveyor. The model takes into consideration the impact exerted on the energy costs for transporting a loose cargo by the magnitude and character of change in the feed speed of a cleaning combine and the speed of the conveyor's chain.

By taking into consideration the built mathematical model, we acquired data on a change in the input cargo flow and the loading of a mine face scraper conveyor over time at forward and backward motion of the combine. These results, obtained for the conditions of transporting broken rock mass at constant (rated) speed, are shown in Fig. 3.



a

b

Fig. 3. Change in the input cargo flow *q*, t/s, loading of mine face conveyor *m*, *t*, and specific energy costs *W*, kW·h/(t·km), for cargo transportation along a coal face over time when cutting a coal strip: *a* — forward motion of the combine, *b* — backward motion of the combine for the conditions of experiment

Fig. 3 shows that the loading of a mine face scraper conveyor, generated by the input flow, which in turn is predetermined by the feed speed of a cleaning combine, is non-uniform over time and varies in the range (0...21) t with a coefficient of variation of 0.53. Because a change in the cleaning combine's feed speed is random in character, the input cargo flow, the loading of a scraper conveyor, and specific energy costs for cargo transportation along a coal face are also the random variables. At maximum possible workload of the conveyor KSD27 with a length of 260 m, 65 tons, the conveyor runs underloaded, which confirms data from experimental study. The consequence is the high specific energy costs for coal transportation along a coal face, reaching the magnitude of 37 kWh/(t·km), or 9.6 kWh/t, which is 6.3 times higher than the maximum value for specific energy consumption required to destroy coal (1.53 kWh/t).

The following trends have been observed:

a) the large values for an input cargo flow and the distant position of a combine relative to the bottom window along a coal face are matched with the large values for conveyor loading;

b) the large values for a cargo flow and the conveyor loading are matched with the lower values for specific energy consumption for transportation.

An analysis of Fig. 3 reveals that at backward motion of the combine one observes the larger values for the maximum conveyor loading than those at forward motion: 21 tons and 18 tons, respectively. In this case, the pan line of a mine face scraper conveyor is underloaded due to the high performance reserve of a scraper conveyor of the cleaning combine. At a maximum conveyor loading of 65 tons, its pan line is loaded during forward motion of the combine by 28 % and 32 %, respectively. The result of the scraper conveyor's underloading along its length and receiving capacity is the high specific energy costs for cargo transportation along a coal face, which, under low-performance operation modes of the combine (for example, a cut into the seam), can reach the value of 37 kWh/(t·km).

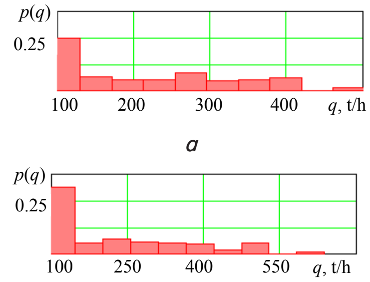
Modeling the process of forming specific energy costs for the transportation of broken coal in a mine face at a constant rate (1.05 m/s) at variable feed speeds of cleaning combine has produced the following results. The weighted specific energy consumption for the transportation of broken coal in a mine face at the forward motion of the combine is 18.1 kWh/(t·km). The weighted specific energy consumption for the transportation of broken coal in a mine face at the backward motion of the combine is 17.4 kWh/(t·km).

5. 3. Development of a mathematical model of the process that forms the output cargo flow from a breakage mine face

An output cargo flow that arrives to the mine's transportation system at a mining enterprise depends on the feed speed of a combine, direction of its movement, and the speed of cargo transportation by a mine face conveyer, and is determined from dependence

$$q_i = HB\rho' \frac{v \cdot v_{pi-n_i}}{60v \pm v_{pi-n_i}}. \tag{25}$$

Formula (25), taking into consideration (5) to (24), is a mathematical model of the output cargo flow formation. A histogram of the output cargo flow distribution at forward and backward motion of the combine and at a constant speed of cargo transportation under conditions of experiment is shown in Fig. 4.



a

b

Fig. 4. Distribution histogram of the output cargo flow from a lava: *a* — forward motion of the combine, *b* — backward motion of the combine

It follows from an analysis of Fig. 4 that the direction of the combine's motion also significantly affects the magnitude and distribution parameters for the output cargo flow. Thus, at a backward motion of the combine under experimental conditions there is an increase in the maximum value for the output cargo flow, by 26.9 % (from 502 t/h at forward motion to 637 t/h), and the mathematical expectation of the latter – by 4.3 % (from 210 t/h at forward motion to 219 t/h). Therefore, a change in the direction of the combine's motion along a coal face significantly changes the non-uniformity of a cargo flow. A given circumstance requires a more detailed study, which is the subject of the further research to be published.

5. 4. Influence of transportation speed and the combine's motion direction on cargo flow and energy indicators for transportation

The results of estimating the influence of coal transportation speed along a coal face on the parameters for an output cargo flow using formulae (1) to (25) are given in Table 3.

Table 3

Mathematical expectation $m(q_{out})$ and coefficient of variation $v(q_{out})$ of the output cargo flow under different operating regimes of the system "combine – conveyor"

v, m/s	Forward motion of the combine		Backward motion of the combine	
	$m(q_{out})$, t/h	$v(q_{out})$	$m(q_{out})$, t/h	$v(q_{out})$
0.5	205	0.51	228	0.73
0.75	208	0.54	222	0.68
1.0	210	0.56	219	0.66
1.25	210	0.57	218	0.65
1.5	211	0.58	217	0.65
1.75	212	0.58	216	0.64
2.0	212	0.59	216	0.64

It follows from an analysis of Table 3:

The speed of cargo transportation along a coal face significantly affects the non-uniformity and the distribution law of output cargo flow from a coal face at a variable feed speed of a cleaning combine, namely:

1. At a forward motion of the combine under experimental conditions:

1. 1. Reducing the speed of transportation from 1 m/s to 0.5 m/s entails reducing the mathematical expectation and the coefficient of variation for an output cargo flow from 210 t/h to 205 t/h (by 2.4 %) and from 0.56 to 0.51 (by 8.9 %), respectively.

1. 2. Increasing the speed of transportation from 1 m/s to 2 m/s leads to an increase in the mathematical expectation and the coefficient of variation for an output cargo flow from 210 t/h to 212 t/h (by 1.0 %) and from 0.56 to 0.59 (by 5.4 %), respectively.

2. At a backward motion of the combine under experimental conditions:

2. 1. Reducing the speed of transportation from 1 m/s to 0.5 m/s entails increasing the mathematical expectation and the coefficient of variation for an output cargo flow from 219 t/h to 228 t/h (by 4.1 %) and from 0.66 to 0.73 (by 10.6 %), respectively.

2. 2. Increasing the speed of transportation from 1 m/s to 2 m/s reduces the mathematical expectation and the coefficient of variation for an output cargo flow from 219 t/h to 216 t/h (by 1.4 %) and from 0.66 to 0.64 (by 3.0 %), respectively.

A change in the speed of cargo transportation at a mine face conveyor changes the output cargo flow distribution law, which in turn affects the non-uniformity and the character of change in the output cargo flow from coal face at a change in the speed of transportation at a mine face conveyor significantly influences the direction of a cleaning combine's motion.

Therefore, to reduce the non-uniformity of an output cargo flow from coal face, it is appropriate to decrease the speed of cargo transportation at a scraper conveyor at the combine's forward motion. Reducing the speed of cargo transportation at a mine face conveyor at the combine's backward motion under experimental conditions would lead to the increased non-uniformity in an output cargo flow from the breakage face.

Fig. 5 shows dependences of the weighted specific energy costs for the transportation of coal by a mine face scraper conveyer on the conveyor's chain speed at the combine's forward and backward motion at actual feed speed. Within the range of values for the chain's speed [0.5; 2] m/s the dependence of the weighted specific energy costs for the transportation of coal by a mine face conveyer in the first approximation is linear. In addition, at the combine's backward motion the weighted specific energy costs for the transportation of coal by a mine face conveyer are 10–20 % lower than those at forward motion. This is due to the large filling of the conveyor at the combine's backward motion, because of the co-direction of the combine's feed speed vectors and the speed of the conveyor's chain.

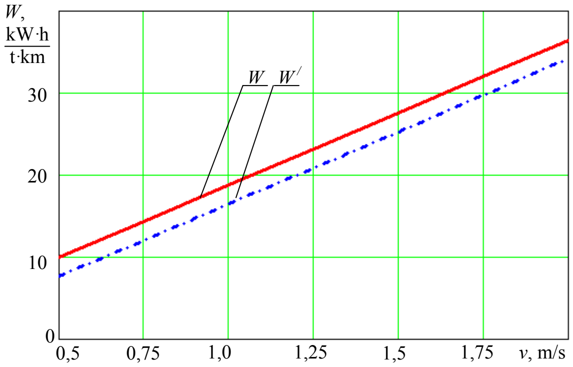


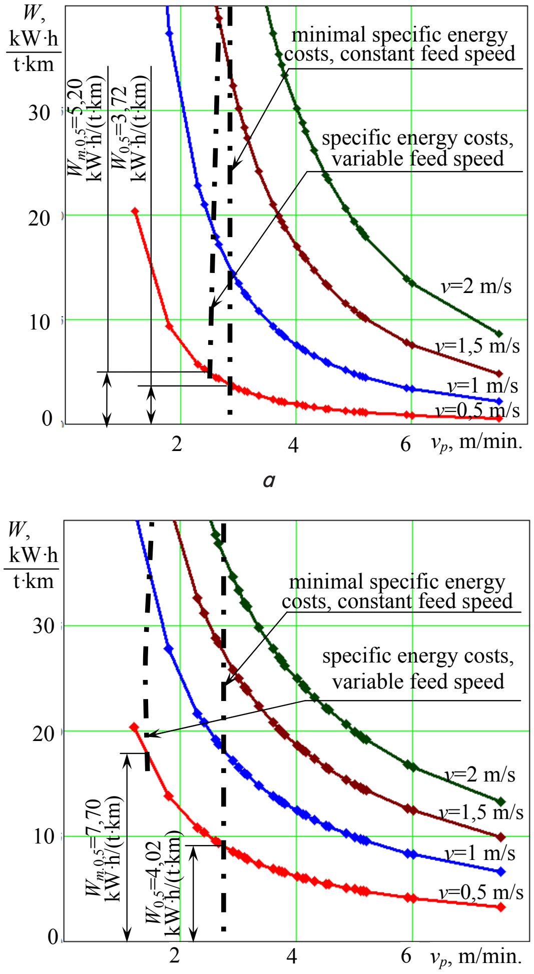
Fig. 5. Dependence diagrams of the weighted specific energy costs for coal transportation along a coal face on speed of the mine face conveyer's chain at variable feed rate of the combine: W are the weighted specific energy costs for transportation at the combine's forward motion; $W^{/}$ are the weighted specific energy costs for transportation at the combine's backward motion

It follows from an analysis of Fig. 5 that the dependence of the weighted specific energy costs for coal transportation by a mine face scraper conveyer on the conveyor's chain speed is linear in nature over a wide range of values for the chain's speed. Thus, at a random speed of the cleaning combine a relative decrease in the specific energy consumption for the transportation of cargo by a mine face conveyer is determined by a relative decrease in the chain's speed.

Fig. 6 shows dependences of specific energy costs for coal transportation along a coal face on the combine's feed speed at different speeds of the conveyor, as well as the minimum and actual weighted specific energy costs for cargo transportation.

It follows from an analysis of Fig. 6 that specific energy costs for coal transportation along a coal face are proportional to the speed of a mine face scraper conveyer and are inversely proportional to the feed speed of a cleaning combine.

At the maximum possible constant feed speed of the cleaning combine v_p=7.5 m/min. an increase in the speed of the conveyor from 1.0 m/s to 2.0 m/s (by 2 times) would lead to an increase in specific energy costs for coal transportation along a coal face from 2.2 kWh/(t·km) to 8.6 kWh/(t·km), that is by 3.9 times, at forward motion, and from 3.3 kWh/(t·km) to 6.6 kWh/(t·km), that is by 2.0 times, at backward motion.



a

b

Fig. 6. Dependences of specific energy costs for coal transportation along a coal face on the combine's feed speed at different speeds of the conveyor's chain: *a* — forward motion, *b* — backward motion

Reducing the speed of the conveyor under the conditions set out above from 1.0 m/s to 0.5 m/s (by 2 times) would lead to a decrease in the specific energy costs for coal transportation along a coal face from 2.2 kWh/(t·km) to 0.6 kWh/(t·km), that is by 3.7 times, at forward motion, and from 3.3 kWh/(t·km) to 1.7 kWh/(t·km), that is by 1.9 times, at the combine's backward motion.

Reducing the assigned feed speed of a combine (provided the uniformity of the latter) from a maximum value under experimental conditions to a minimum value, from 7.5 m/min. to 1.2 m/min. (by 6.25 times) leads to the hyperbolic increase in the energy costs for coal transportation coal by a scraper conveyor along a coal face. Thus, for the combine's forward motion at the conveyor speed of 1.0 m/s specific energy costs for cargo transportation would increase from 2.2 kWh/(t·km) to 81 kWh/(t·km), that is by 37 times. At the combine's backward motion at the conveyor speed of 1.0 m/s specific energy costs for cargo transportation would increase from 3.3 kWh/(t·km) to 20.6 kWh/(t·km), that is by 6.2 times.

Therefore, a minimum value for the specific energy costs for coal transportation along a coal face is matched with the constant maximum possible feed speeds of a cleaning combine and the lowest possible speeds of a mine face scraper conveyer.

Results of the estimation of influence of the coal transportation speed along a coal face and the non-uniformity in the speed of combine's displacement on the weighted specific energy costs for the transportation of cargo using the built mathematical model are given in Table 4. It contains values for the weighted specific energy costs for coal transportation by a mine face scraper conveyer for the combine's forward and backward motion for the following operating modes of the system "combine-conveyor".

R1 is the actual feed speed of a combine, the conveyor's speed is constant, rated, – $v_{П} \in [1,2;7,5]$ m/min. (mathematical expectation $m(v_p)$=2.86 m/min.), $v=v_H$=1.05 m/s;

R2 is the actual feed speed of a combine, the conveyor's speed is constant, reduced by 12 % relative to the rated value, – $v_{П} \in [1,2;7,5]$ m/min. (mathematical expectation $m(v_p)$=2.86 m/min.), v=0.95 m/s;

R3 is the constant feed speed of a combine, the speed of a mine face conveyor v=0.75 m/s;

R4 is the constant feed speed of a combine, the speed of a mine face conveyor $v=0.5v_H$=0.53 m/s;

R5 is the constant feed speed of a combine, v_p= =2.86 m/min.=const, v=0.42 m/s; 0.45 m/s=min{v}.

Adjustment of the conveyor's chain speed to the magnitude and character of change in the combine's feed speed [21] refers to the alignment between a conveyor's chain speed and the feed speed of a cleaning combine. The adaptation is carried out taking into consideration the actual cargo flow at a conveyor and a direction of the combine's motion, which ensures a rational mode for the operation of a cleaning combine [22] and reduces energy intensity of the broken coal transportation along a coal face.

Moreover, the speed of a mine face conveyer when it is adapted for the combine's displacement speed would depend not only on the current value for the feed speed of the combine (a direct proportionality), but also on the direction of the combine's motion. At the combine's forward motion

$$\min\{v\} = v_{nom}\frac{v_{p.m}}{v_{p.\max}}\frac{60v_{nom}}{60v_{nom}+v_{p.m}} = \\ =1{,}05\frac{2{,}86}{7{,}5}\frac{60\cdot 1{,}05}{60\cdot 1{,}05+2{,}86}=0{,}42,\quad \text{m/s;} \qquad (26)$$

at the combine's backward motion

$$\min\{v\} = v_{nom}\frac{v_{p.m}}{v_{p.\max}}\frac{60v_{nom}}{60v_{nom}-v_{p.m}} = \\ =1{,}05\frac{2{,}86}{7{,}5}\frac{60\cdot 1{,}05}{60\cdot 1{,}05-2{,}86}=0{,}45,\quad \text{m/s.} \qquad (27)$$

Table 4

Values for the weighted specific energy costs for transporting broken coal by a mine face scraper conveyor under different operating regimes of the system "combine – conveyor"

Designation of operating regime	Operating regime parameters			Specific energy costs for transporting broken coal by a mine face conveyer, W, kWh/(t·km)	
	displacement speed of the combine, v_p, m/min.	conveyor's chain speed, v, m/s	direction of combine's motion	corresponding to direction of combine's motion	average
R1	$v_p \in [1.2;7.5]$ $m(v_p)=2.86$	$v_{nom}=1.05$	forward motion	18.1	17.8
			backward motion	17.4	
R2	$v_p \in [1.2;7.5]$ $m(v_p)=2.86$	0.95	forward motion	16.3	16.0
			backward motion	15.6	
R3	$v_p=m(v_p)=2.86$	0.75	forward motion	8.37	7.57
			backward motion	6.76	
R4	$v_p=m(v_p)=2.86$	0.53	forward motion	4.19	4.26
			backward motion	4.33	
R5	$v_p=m(v_p)=2.86$	0.42	forward motion	2.63	3.08
		0.45	backward motion	3.53	

It follows from Table 4 that the specific energy costs for coal transportation by a mine face conveyer without adapting its speed to the magnitude and direction of the combine's feed speed significantly exceed specific energy consumption when destroying coal along a coal face. For the constant speed of a mine face conveyor of 1.05 m/s the weighted specific energy costs for coal transportation along a coal face are 17.8 kWh/(t·km) or 4.81 kWh/t This is 5 times larger than the value for specific energy costs for coal destruction.

A rational mode of operation of the system "combine – conveyor" based on the criterion for minimizing the weighted specific energy costs for the transportation of cargo by a mine face conveyer is the combine's operation at a constant speed. The conveyor should run at speed that is adapted to the combine's feed speed, taking into consideration the magnitude of the latter and a direction of the combine's motion. In this case, one expects a decrease in the weighted specific energy consumption for transportation from 17.8 kWh/(t·km) to the value of 3.08 kWh/(t·km), that is by 5.8 times, for a cycle of coal extraction along a coal face, in comparison with the experimental conditions. This amounts to 0.84 kWh/t, which is commensurate to the specific energy costs for coal destruction.

Thus, the maximum potential energy saving when adapting the speed of mine face scraper conveyer to the speed of the combine is 17.8–3.08=14.72 kWh/(t·km) or 3.97 kWh/t.

A given circumstance should be taken into consideration when choosing a technique to adjust the speed of a mine face conveyor and a cleaning combine along a coal face.

6. Discussion of results of studying the output cargo and specific energy costs for cargo transportation

The main benefit of our research is the establishment under representative conditions of intensive mining of the character of dependence of the weighted specific energy costs on coal transportation by a scraper conveyor on its speed, as well as on speed of the combine's displacement. We indicated the existence of reserves to reduce energy consumption for mine transportation by adjusting the transporting speed.

The main result of this study is the construction of a mathematical model that describes the process of forming an output cargo flow from a coal face and the weighted specific energy costs for cargo transportation by a mine face scraper conveyor.

Shortcomings of the study are as follows. There are no data from the experimental study on the measurement of current values for power of the drive in a mine face scraper conveyor, corresponding to the position of a cleaning combine at a mine face. This complicates the task on assessing the adequacy of the built mathematical model for forming the weighted specific energy costs for the transportation of broken coal by a mine face conveyer.

The data obtained could be used in the following areas:

– conceptual design of highly efficient resource-saving transporting machines, transportation systems and technological complexes for intensive coal mining;

– creation of CAD systems for conveyor industrial transport at mining enterprises engaged in intensive extraction of useful minerals;

– elaboration of practical recommendations on the ways to reduce energy consumption for cargo transportation at an industrial enterprise.

The areas for the further research are:

– carrying out a set of experimental and theoretical studies into the operation modes of a scraper conveyor to apply the results obtained in this work for various mining-geological and technical conditions for coal extraction;

– substantiating a technique and an algorithm to adjust the chain's speed of a mine face conveyer to the feed speed of a cleaning combine, specifically as a mechatronic complex, based on the criterion of energy consumption for transportation;

– substantiating the space and the design parameters, the optimization criteria and development of the objective function for the optimization of a scraper conveyor with adjustable drive as a mechatronic subsystem;

– conducting a research to establish the effect of the technological workflow of coal extraction, as well as separate technological operations on extraction, on the output cargo flow from a coal face and the weighted specific energy costs for coal transportation;

– conducting a set of studies to establish the effect of the non-uniformity in a cargo flow and in the distribution of cargo mass at a conveyor on the dynamic loading and resource in the elements of its structure;

– development of a system of controlled drive, a system of adaptive control over the system "combine – conveyor", which would ensure the adjustment of speeds between a mine face conveyer and a cleaning combine.

Solving these tasks would contribute to resolving the issue on the intensification of coal mining in terms of creating reliable and effective scraper conveyors at the new technical level for the mining industry. For scraper conveyors that operate in a tandem with cleaning combines, along with diagnosing and control over equipment without disconnecting from the network, that could ensure the optimization of energy costs for transportation, as well as the resource for their constituent elements.

7. Conclusions

1. The feed speed of a combine is highly non-uniform: a mathematical expectation of the feed speed of a combine under experimental conditions is 2.86 m/min. When indexing the random process using a time parameter, the coefficient of variation is 0.45. When cutting a strip of coal along a coal face, the cleaning combine utilizes the conveyor's performance reserve by 43 %.

2. We have developed the structural and mathematical model for the formation of an output cargo flow and the weighted specific energy costs for transportation. The model takes into consideration the technological and structural parameters for the process of coal excavation and transportation at a mine face. Parameters for the distribution of an output cargo flow at the combine's forward motion are: a mathematical expectation is 210 t/h, the coefficient of variation is 0.56; at backward motion, respectively, 219 t/h and 0.66. The weighted specific energy costs for coal transportation at a mine face at the combine's forward motion are 18.1 kWh/(t·km); at backward motion, 17.4 kWh/(t·km).

3. Optimization of operation of a mine face conveyer, considering the adjustment of the conveyor's speed to the magnitude and the character of change in the speed of a combine, a cargo flow and a direction of the combine's motion makes it possible to significantly decrease specific energy costs for transporting coal along a coal face. The speed of cargo transportation greatly affects the parameters for the distribution of an output cargo flow from a coal face. When assigning the conveyor speed, adjusted to the magnitude and the character of the combine's speed, one expects to reduce specific energy costs for transportation by 5.8 times for a cycle of coal extraction along a coal face, in comparison with the conditions for experiment. A maximum potential energy saving when adjusting the speed of a mine face scraper conveyor to the speed of the combine is 17.8–3.08=14.72 kWh/(t·km) or, to the experimental conditions, 3.97 kWh/t.

These circumstances should be taken into consideration in the design and development of extracting and transporting equipment at the new technical level, specifically to adapt the speed of a mine face scraper conveyer to the feed speed of a cleaning combine.

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DEVELOPMENT AND INVESTIGATION OF THE REDUCED MATHEMATICAL MODEL OF THE PROCESS OF BAKING CARBON PRODUCTS

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Розробка оптимального керування процесом випалювання вуглецевих виробів передбачає врахування впливів характерних зон печі та однорідності температурного поля по заготовкам. Дане твердження вимагає розробку математичної моделі печі випалювання з розподіленими параметрами. Відомо, що час розрахунку таких моделей досить великий, а відтак їх застосування в реальному часі не можливе. Відповідно до вище сказаного для подальшої розробки системи оптимального керування процесом випалювання існує потреба у спрощенні повної математичної моделі, що забезпечує потрібний час розрахунку.

Розроблена та досліджена спрощена математична модель процесу випалювання, яка відрізняється від відомих моделей меншим часом розрахунку при дотриманні поставлених вимог щодо її точності.

Встановлено, що для випадків використання n>15 перших базис-векторів забезпечує виконання обмеження по допустимій похибці апроксимації значень коефіцієнтів Фур'є. Можливість вибору оптимальної структури ідентифікаційних моделей визначає можливість отримання температурних знімків спрощеної математичної моделі з необхідною точністю.

Отримані результати дозволяють гнучко обрати варіант спрощеної математичної моделі відповідно до технічних можливостей обчислювальної техніки.

Враховуючи, що у процесі випалювання вуглецевих виробів визначальними температурами є температури заготовок, то для дослідження якості спрощених моделей були обрані Control points лише по заготовкам.

Оскільки процес випалювання вуглецевих виробів складається з трьох основних етапів, то для адекватного моделювання такого процесу було реалізовано три спрощені математичні моделі даних етапів.

Дослідження точності спрощених моделей включало порівняння значень температур, розрахованих за спрощеною моделлю, з температурами, обчисленими за початковою моделлю, яка у даному випадку розглядалася як генератор експериментальних даних

Ключові слова: процес випалювання, температурні поля, метод розділення змінних, вуглецеві вироби

1. Introduction

Manufacturing of carbon products is an extremely power-intensive and therefore costly technological process. One of the key stages in the whole technological process is baking carbon products, carried out in a closed-top multi-chamber furnace. The multi-chamber baking furnace is an object with extremely high energy consumption and even an insig-