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CONTROLLED OBJECT STRUCTURAL IDENTIFICATION IN THE PRODUCTION UNIT OPTIMAL CONTROL PROBLEM

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Introduction. *The basic way of ensuring high profitability of coal production is mining operations concentration and intensification. Coal bed methane content, progressive mineral production flowsheets, and highly productive longwall mining equipment lead to the increased methane content of stopes, gassings downtimes, and significant economical wastes.*
Research methodology. *The given contradiction can be settled by means of optimal control over the production unit which provides for simultaneous provision of high productivity and aerological safety. With the use of known descriptions of aerological, technological, and geogasdynamic processes the structure of coal production process simulation model is worked out. It is suggested to describe gas mixture motion and methane emission out of various sources in a longwall face in discrete time and space. The analysis is fulfilled of gas sources influence in general airgas flow. The process of forming a fluid flow in a coal bed is examined and the possibility for the detailed description of gas desorption process is assessed.*
Results. *The article analyzes the model forms of gas emission out of a coal bed and out of loose coal, and airgas flow motion in a longwall face; adequate, to the author's opinion, model structures are suggested. The correlation between methane emissions out of various sources and process equipment operating modes is discovered. As a result, sufficient amount of variables is determined and coal production process parametric simulation model is formed to develop the winning machine optimal control system.*

Key words: *stoping area; gas emission; methane; identification; model.*

Aim. High methane-bearing capacity of stopes defined by the methane content of the developed coal beds, progressive coal production flowsheets, and highly productive longwall sets of equipment is a reason for hazardous aerological situations – gassings which lead to winning equipment downtimes and, consequently, to loss of coal producers economic efficiency [1]. Longwall set of equipment optimal control problem reduces to productivity maximization when excluding gassings.

Methodology. Optimal control system synthesis requires structural and parametric identification of coal production process. Fig. 1 reveals the developed generalized model of a production unit as a controlled object. Henceforward, if additional determination is not given: bold type refers to vectors and matrices, normal type refers to scalars; u and S – control and state; Q (m^3/s), C (% volume fraction), M (N·m), p (Pa), v (m/s), J (kg/s), and $\{x, y, z\}$ (m) – consumption of gas mixture (ГС), concentration, moment, pressure, velocity, productivity, and coordinates; P and T (s) – probability density function and time constant; superscripts “З”, “СН4” refer to the prescribed value, methane, “П” and “Р” – shearer loader's feed drive and cutting drive; subscripts “ПОСТ” and “ИСХ” – intake flow and outgoing flow, “УП”, “ВП”, “Л”, and “КР” – coal bed, worked out area, longwall face, and roof, “МК”, “К”, and “ОК” – mechanized support, face conveyor, and shearer loader, “ВУ”, “ГОС”, and “ДГС” – fan units (and equipment), gas-suction plant, and degassing system, “СОПР” – stoping face resistance against the effect of a shearer loader, "НП" is a normative threshold. If not specified, all variables are time functions and their full listing in the form of $y(t)$ is reduced to y.

Production unit complete optimal control system (СУ) should possess a transfer operator in the form of $[\mathbf{u}_{ОК}, \mathbf{u}_{УП}, \mathbf{u}_{К}, \mathbf{u}_{ГОС}, \mathbf{u}_{ДГС}, \mathbf{u}_{ВУ}, \mathbf{u}_{МК}] = \mathbf{G}_{СУ}(\mathbf{S}_{ОК}, \mathbf{S}_{УП}, \mathbf{S}_{К}, \mathbf{S}_{ГОС}, \mathbf{S}_{ДГС}, \mathbf{S}_{ВУ}, \mathbf{S}_{МК}, \mathbf{S}_{Л})$, where $\mathbf{G}_{СУ}$ is a transfer operator of СУ. By a state $\mathbf{S}$ is meant a quantity of variables and parameters characterizing the corresponding element of a controlled object or a process and can be controlled by СУ; by a control $\mathbf{u}$ is meant a quantity of controlling impacts on each element of a controlled object. However, since many state variables are difficult for measuring, control over ВУ, ГОС and ДГС is characterized by significant lag [2], МК control is connected with lightly regulated and poorly controlled process of КР destruction, control over gas emission out of УП is based on its properties (degassing) alternation and has long term of realization, and К control is carried out depending on ОК operating parameters, then production unit rational control capabilities are connected with ОК control channels which are characterized by maximum operation speed and high sensitivity. In this case optimal control problem can be formulated as follows:

$$\begin{cases} J_{ОК}(\mathbf{u}_{ОК}) \to \max; \\ P\left(C^{CH4} > C^{CH4}_{НП}\right) \le P^{з}(h); \\ \mathbf{u}_{ОК} = \mathrm{u}_{ОК}(J^{з}_{ОК}, \mathbf{S}_{Л}, \mathrm{S}_{ОК}, \mathrm{S}_{К}, \mathrm{S}_{УП}, \mathrm{S}_{ВУ}, P^{з}(h)), \end{cases} \qquad (1)$$

where $P(C^{CH4} > C^{CH4}_{НП})$ – a probability that methane content exceeds НП; $P^{з}$ – a given value of an acceptable exceedance probability $C^{CH4} > C^{CH4}_{НП}$ depending on the quantity of gassings h.

In order to develop СУ (1) it is necessary to control, assess, and forecast the content of methane in a longwall face, for this purpose the identification of aerogasdynamic processes in stopes is required.

Analysis and discussion. *Gas balance equation and gas mixture motion.* Fig. 2 introduces a computational scheme and a stoping model. Stoping face is divided into spatial discretes $\Delta L = L_з / n$, where $L_з$ – longwall face (stope) length, m; n – discretes quantity (enumeration in the direction of ГС motion). Since there is a tendency towards the decrease in the width of a face working space, then methane emissions out of enclosing rock $\mathbf{Q}_{ПОР}$ are neglected because of their relatively small share (0.1–0.01% of total gas emission in a longwall face [3]) and the processes of gas emission in $\{x, y\}$ plane are further considered.

In the model, each discrete is considered as a functional block ensuring transfer and mixing of ГС which is formed at its inlet:

$$\mathbf{Q}_{ИСХ,i} = G\left(\mathbf{Q}_{ИСХ,(i-1)} + \mathbf{Q}_{УП,i} + \mathbf{Q}_{К,i} + \mathbf{Q}_{ВП,i}\right), \qquad 1 \le i \le n, \qquad (2)$$

where $\mathbf{Q} = [Q^{N2}, Q^{O2}, Q^{CO}, Q^{CO2}, Q^{NO}, Q^{NO2}, \ldots]$; N2, O2, CO, CO2, NO, NO2 – chemical formulae of gases composing ГС; G – transfer operator describing transfer and mixing of ГС. For the first and the last discrete correspondingly:

$$\mathbf{Q}_{ИСХ,(i-1)} = \mathbf{Q}_{ПОСТ}, \qquad i = 1; \qquad (3)$$

$$\mathbf{Q}_{ИСХ,n} = \mathbf{Q}_{ГОС} + \mathbf{Q}_{ИСХ}, \qquad i = n, \qquad (4)$$

where $\mathbf{Q}_{ГОС} = k_{ГОС}\,\mathbf{Q}_{ИСХ,n}$ and $\mathbf{Q}_{ИСХ} = (1 - k_{ГОС})$; $\mathbf{Q}_{ИСХ,n}$ – consumption of ГС removed by ГОУ, and in the outgoing flow of a stoping area; $k_{ГОС}$ – coefficient modeling the separation of a flow coming out of a longwall face.

Increased stope load leads to the alteration in the weights of separate sources of gas emission into the space of a stope. Then, $\mathbf{Q}_{УП}$ increases up to the value determined by the characteristics of УП itself $Q_{УП}^{max}$, $\mathbf{Q}_{К}$ increases not only in proportion to the output, but also by means of increasing gas content of coal detached from ground, and $\mathbf{Q}_{ВП}$, with proper design and correct ДГС operation, becomes indiscernible. In this connection, under intensive recovery gas balance of the face working space will be made up of three sources: $\mathbf{Q}_{ПОСТ}$, $\mathbf{Q}_{УП}$, and $\mathbf{Q}_{К}$. Great influence on $\mathbf{Q}_{УП}$ and $\mathbf{Q}_{К}$ is made by the displacement velocity of ОК which carries out the recovery: because of change in the amount of removed coal and increase in the area of a desorbing surface through which almost all free sorbed gas comes out, coal degassing is more intense. Thus, gas emission at production unit depends on the parameters of incoming ГС and longwall face advance rate determined by $v_{ОК}^{П}$ ($J_{ОК}$), and on the time which passed from the moment of bed stripping with ОК operating body.

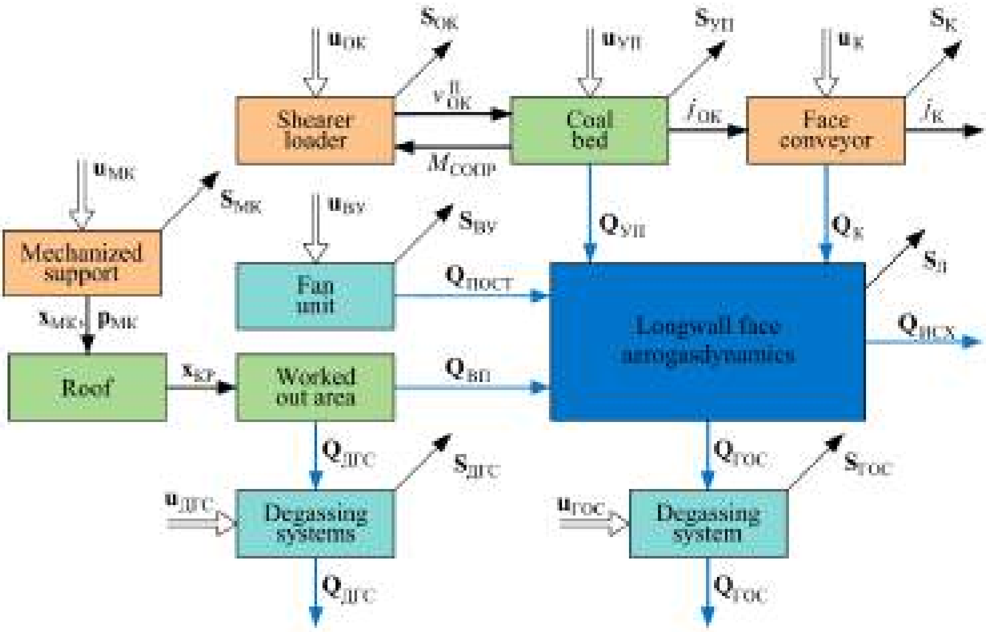

Fig. 1. Generalized structure of a production unit model as a controlled object
Рис. 1. Обобщенная структура модели добычного участка как объекта управления

Operator G in (2) describes aerogasdynamics and is generally realized with mathematical physics equations in partial derivatives of various types [4], however for engineering purposes and in СУ such approach is not applicable. In [5] mathematical description of mine workings and their typical connections in the form of the systems of integro-differential (differential) and algebraic equations is suggested, together with the methods of setting up the equations of gas balance for a group of mine workings, at inputs and outputs of which gas consumption and content is regulated. At that with the account of a range of suppositions for a section of a mine working with the length l, m:

$$Q_{ИСХ,i}(s) = G(s)Q_{ИСХ,(i-1)}(s) = \frac{\exp(-\tau(t)s)}{(T_C s+1)^c} Q_{ИСХ,(i-1)}(s), \qquad (5)$$

where T_C – mixing time constant, s; $\tau(t) = l / v(t)$ – time of ГС displacement along the mine working, s; $v(t)$ and $Q(t)$ – ГС velocity and consumption, $v(t) = Q(t) / 60S$;

S – mine working section area, m^2; c = ceil(l / ΔL), ceil – function of mathematical rounding; s – Laplace operator. Similar approach is described in [6].

Coal bed. Coal bed (УП) represents inhomogeneous fractured-porous sorbing media removal of which leads to a range of aerogas and thermophysical processes generation and development within the limits of a mining extracted area [7]: filtration and diffusion gas transfers, interbedding combustion, and coal gasification.

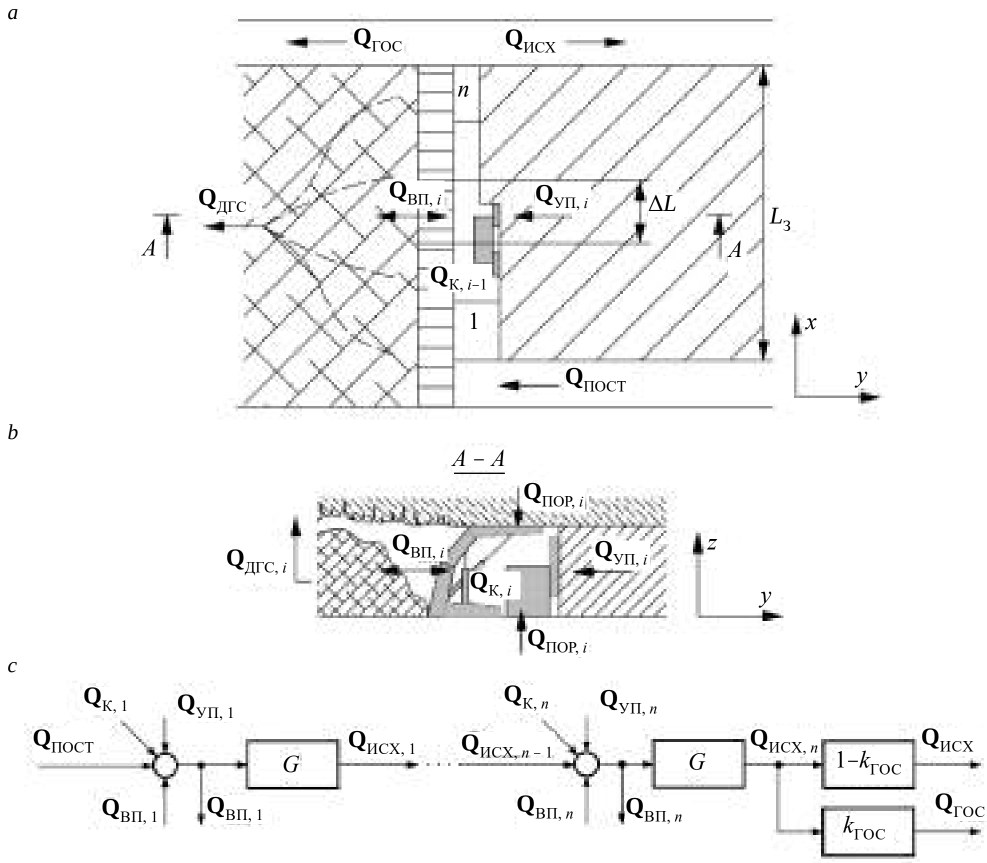

Fig. 2. Longwall face aerogasdynamics model:
a, *b* – scheme of ГС flows in a stope, *c* – structure of longwall face aerogasdynamics model
Рис. 2. Аэрогазодинамическая модель лавы:
а, *б* – схема потоков ГС в очистной выработке; *в* – структура аэрогазодинамической модели лавы

Fluid flow, with regard to in the impact of stoping processes on the massif, is closely interconnected with the stresses in УП. Out of blocks which discretize a coal massif, methane inflows to the fissures by means of diffusion. Flow of ГС (methane) along the fissures is determined by the value of rock pressure and is described as a filtration process with Darcy's law [8]: $v_\Phi = Q_{\text{УП}}^{\text{СОР}} / S_\Phi = k_{\text{ПР}} \Delta p_\Gamma (\mu \lambda)^{-1}$, where v_Φ – ГС filtration linear velocity; $Q_{\text{УП}}^{\text{СОР}}$ – volume flow rate of sorbed ГС in a gas bearing coal massif; S_Φ – filtration block cross section area, m^2; $k_{\text{ПР}}$ – coal massif permeability coefficient, m^2; μ – ГС dynamic viscosity, Pa · s; Δp_Γ – pressure drop causing filtration through porous medium with the length λ, m. Then for gas volume flow rate $Q_{\text{УП}}^{\text{СОР}} = S_\Phi k_{\text{ПР}} \Delta p_\Gamma (\mu \lambda)^{-1}$. This approach supplemented with the equations of diffusion on the basis of Fick's law seams well grounded and its use in СУ requires comprehensive information on the properties of УП $S_{\text{УП}}$ in $\{x, y, z\}$ space. Existing technologies allow determining blocky structure (assess S_Φ and λ) and pressure gradients Δp_Γ in УП [9] which is necessary but inadequate to build a model and СУ based on Darcy's law. Because of difficulty determining $k_{ПР}$ and μ in high-speed geodynamic and mining-technological conditions and unavailable data on sorption capacity parameters of the coal block, diffusion coefficient, and other methane motion characteristics which were examined at calculations, the use and the implementation of this model of methane motion in УП and its emission at this stage is impeded but possible if УП isotropy is accepted and average for УП values of $k_{ПР}$ and μ are used at calculations.

Hereafter alternative approach is used which considers only face working part of УП with ОК coverage. Researches in the field of methane emission from the surface of УП consider general regularity between the degree of coal degasation in a massif and increase in velocity $v_{ОК}^{П}$ which totally corresponds to stresses alternation in УП near the face. The highest methane emission intensity is observed at the freshly exposed УП surface near the operating body (t_0, $x_{ОК}^{0}$) and is defined by coal maximum volume gas content which $Q_{УП,i}^{\max}$ (fig. 3, *a*) depends on.

In front of ОК there is the rise of gas emission (*curve 1*) conditioned on the redistribution of stresses in УП in the connection with ОК advance along the face $\tau_i < \tau_{0,i}$; then there is a fall in the intensity of gas emission (*curve 2*) at the freshly exposed surface:

$$Q_{УП,i} = \begin{cases} Q_{УП,i}^{\max} \exp\left((\tau_{0,i} - \tau_i)/T_{1,i}\right), & \tau_i < \tau_{0,i}; \\ Q_{УП,i}^{\max} \exp\left((\tau_{0,i} - \tau_i)/T_{2,i}\right), & \tau_i > \tau_{0,i}, \quad \tau_i \to \infty, \end{cases} \quad (6)$$

where $T_{1,i}$ and $T_{2,i}$ are УП draining time constants typical for i discrete before and after ОК operating body affects УП, which depend on $p_Г$ and on the coefficient of $k_{A,I}$ coal massif draining; τ_i, $\tau_{0,i}$ are local time and the term the operating body of ОК is in *i* discrete [7], $\tau_{i+1} = \tau_i + \Delta L / v_{ОК}^{П}$. Correlation (6) is verified in [4]. For $Q_{УП,i}^{\max}$ it is possible to write $Q_{УП,i}^{\max} = J_{ОК}\, k_{УП}\, m\, \rho^{-1}$, where $k_{УП}$ – coefficient of methane transfer from УП surface; *m* and ρ – porosity and density, kg/m^3, of coal in a massif, then the model of gas emission out of УП will be written as:

$$Q_{УП,i} = \begin{cases} J_{ОК} k_{УП} m \rho^{-1} \exp\left((\tau_{0,i} - \tau_i)/T_{1,i}\right), & \tau_i < \tau_{0,i}; \\ J_{ОК} k_{УП} m \rho^{-1} \exp\left((\tau_{0,i} - \tau_i)/T_{2,i}\right), & \tau_i > \tau_{0,i}, \quad \tau_i \to \infty. \end{cases} \quad (7)$$

Fig. 3, *b* displays emission in the neighboring discretes along the face: dotted line refers to physical time, and bold vertical lines refer to methane emission in corresponding discretes for this time point. At that, maximum gas emission $Q_{УП,i} = Q_{УП,i}^{\max}$ at the point $\tau_i = \tau_{0,i}$ corresponds to stoping in real time $t = \tau_i + \tau_{0,i}$ in *i* discrete (second from the top graph at fig. 3, *b*).

The given approach allows to determine gas emissions out of the face of stope within the limits of a discrete based on the УП parameters ($k_{УП}$, *m*, ρ, and $T_{1,i}$ and $T_{2,i}$, depending on $p_Г$ and k_A) and the characteristics of ОК operation ($J_{ОК}$, $v_{ОК}^{П}$ and $x_{ОК}$).

Shearer loader. The base of a shearer loader model make up cutting drives and feed drives (fig. 4); their mathematical description creates no problems under sufficient initial information [10]. Interaction between these two drives and УП requires determining the moments of coal resistance against destruction which happen when ОК operating body affects УП and prevent the development of dynamic phenomenon.

One of methods is based on *t* simultaneous solution of the equations $F_{СОПР}^{Р} = 150\, r\, f\, k_{ОТ}$ [11] and $r^2 - 2rR_{ОК}^{Ш} + 2\delta_С (R_{ОК}^{Ш} z \omega_{ОК}^{Р})^2 (4\pi v_{ОК}^{П})^{-2} = 0$ [12], where $F_{СОПР}^{Р}$ – cutting resistance force, N · m; *f* – hardness coefficient according to

Protodyakonov's scale; r – УП cutting depth, m; $k_{ОТ}$ – coefficient of coal sloughing characterizing УП and enclosing rock, strength, bedding angle, face advance rate, operating body coverage width, and mine working length, kg/s^{-2}; $R_{ОК}^{Ш}$ – cutting screw radius, m; δ_C – chip thickness, m; z – an average number of cutters in a cutting line.

However, all roots of the last formula are nonnegative rational numbers which prevents from getting unambiguous solution, and because of the smallness of $v_{ОК}^{П}$ and $\omega_{ОК}^{Р}$ (for example, for ОК Eickhoff SL 300 nominal values are: $v_{ОК}^{П}$ = 0.618 m/s, $\omega_{ОК}^{Р}$ = 0.77 rad/s) the solutions lose their physical significance. Another method [13] takes into account the equality $M_{СОПР}^{Р} = v_{ОК}^{П} k_1$ which is expected in many instances in СУ, where k_1 is a parameter characterizing УП capability to resist against destruction, kg · m/s. On the basis of the presented observations transfer operator $W_{УП}$ (fig. 4) is further described by the equations $M_{СОПР}^{Р} = v_{ОК}^{П} k_1 + \omega_{ОК}^{Р} k_2$ and $M_{СОПР}^{П} = v_{ОК}^{П} k_3$ where k_2 – proportionality factor of cutting speed and cutting resistance moment, kg · m^2/s · rad; k_3 – proportionality factor of feeding speed and feeding resistance moment, kg · m/s.

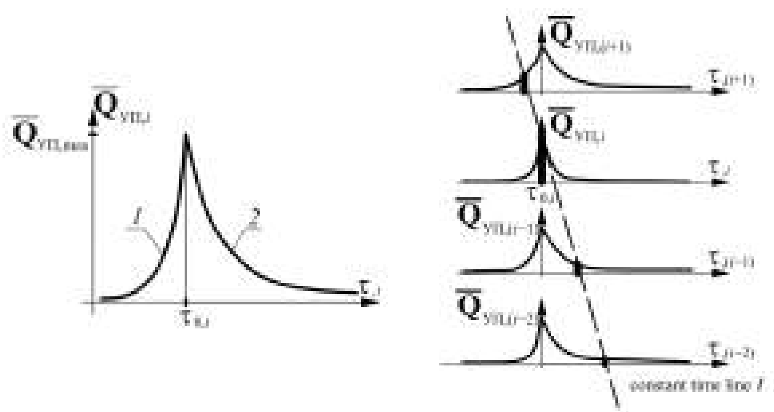

Fig. 3. Gas emission from УП surface:
a – general regularity of methane emission from УП surface; *b* – regularity for the neighboring spatial discretes

Рис. 3. Газовыделение с поверхности УП:
а – общая зависимость выделения метана с поверхности УП; *б* – зависимости для соседних пространственных дискрет

To forecast methane emission in a longwall face it is necessary to control $x_{ОК}$ ($n_{ОК}$) – ОК position (spatial discrete no.), its velocity $v_{ОК}^{П}$ and productivity, kg/s,

$$J_{ОК} = rHv_{ОК}^{П}\rho, \qquad (8)$$

where H – thickness (bed depth) of rock layer, m [12].

Loose coal. In the result of УП destruction loose coal is loaded on the conveyor (К), at that, its insignificant part is left at the machine runway if ОК free running with cleanup is not provided. Space-time character of external actions is defined by the coal winning technology [14].

At the existing face output, gas emission out of loose coal is 10–30% in gas balance of face working space [7]. With the increase of stoping face advance rate conditioned on $v_{ОК}^{П}$, the degree of coal degassing in a massif continually declines, i. e. coal transfers into the loosened state with growing gas content $w_К$ which leads to the rise of $Q_К$. Specific weight of this source in gas balance increases because of the produced coal volume increase

$$\Delta J_{К,i} = \int_0^{t_Д} S_К v_К v_{ОК}^{П} \rho\psi\varphi \left(\Delta L\right)^{-1} dt, \qquad (9)$$

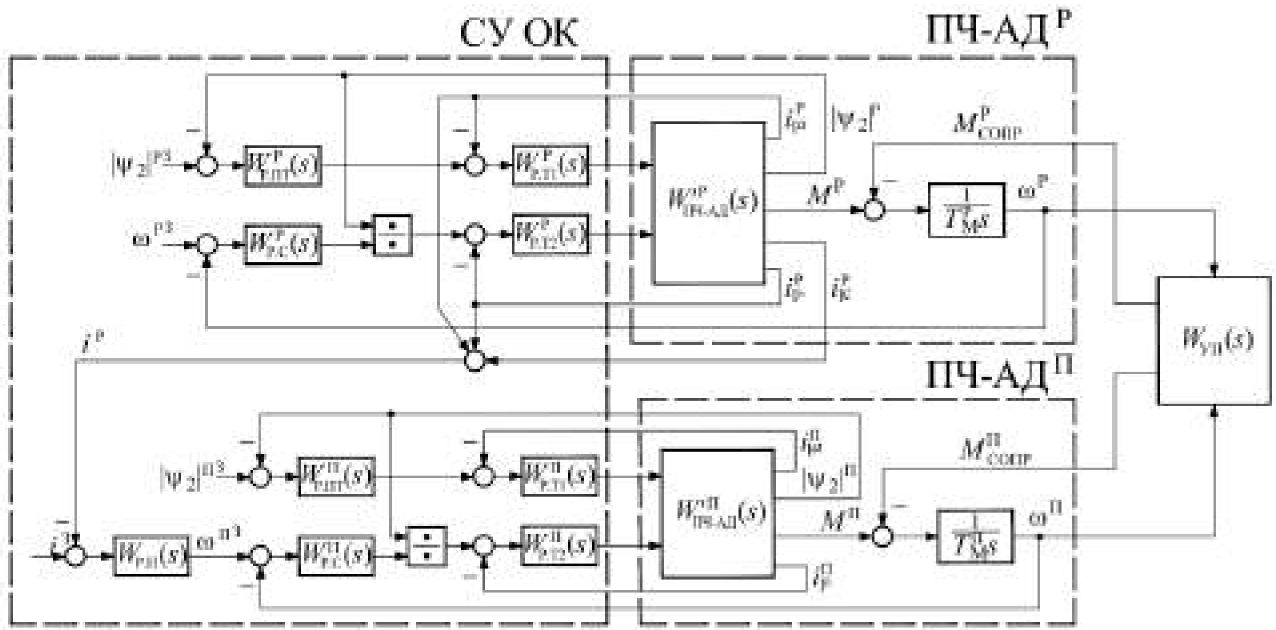

Fig. 4. Structure of a shearer loader model by the example of vector control system:
СУ ОК – shearer loader control system; ПЧ-АД – frequency converter – acynchronous motor; $W_{Р*}$ – controller transfer function: ПТ – flow, Т – current, С – speed, Н – load; $W'_{ПЧ-АД}$ – matrix transfer operator of ПЧ-АД electrics without mechanicals characterized by the time constant $T_М$; $W_{УП}$ – УП transfer operator

Рис. 4. Структура модели очистного комбайна на примере системы векторного управления:
СУ ОК – система управления очистным комбайном; ПЧ-АД – преобразователь частоты – асинхронный двигатель; $W_{Р*}$ – передаточная функция регулятора: ПТ – потока, Т – тока, С – скорости, Н – нагрузки; $W'_{ПЧ-АД}$ – матричный передаточный оператор электрической части ПЧ-АД без механической части, характеризующейся постоянной времени $T_М$; $W_{УП}$ – передаточный оператор УП

where $S_К$ – trough cross section area К, m²; $v_К = f(v_{ОК}^{П})$ – loose coal conveying speed К, m/s; ψ – trough filling rate; φ – coefficient taking into account inclination angle of К.

Increase in the area of gas discharging surface leads to intensive gas emission out of coal at К. Gas content of loose coal decreases by means of diffusion flows motion inside a coal piece directed towards gas discharging surfaces. According to [7] loose coal desorption process is physically identical to УП degassing. Sorbed in ultra- and micropores gas transfers into loose conditions due to the pressure decline in macropores. Along the latter the desorbed methane comes out towards the surface of coal and enters the atmosphere. The difference is in the number of macropores, their lateral dimensions, and length. Loose coal possesses more macropoes, they are wider and shorter, i. e. their resistance against gas diffusion is much lower than in conditions of a coal massif, so desorption process abruptly intensifies. Consequently, loose coal degassing can be described with the same correlations as a coal massif: $w_К = w^{max}\exp(-t / T_3)$, where w^{max} – coal gas content at the moment of its detaching from the massif, m³/kg; T_3 – degassing parameter depending on physical-chemical properties of coal.

Researchers of [15] developed the methods of calculating methane inflow out of loose coal in the course of transportation time at on the basis of differential equation of methane mass transfer with the account of coal granulometric composition (methane inflows into the longwall face grow at the increase of the degree of loos coal grinding) and technological parameters of face operation. As coal piece decomposing into spherical particles with typical intensity of gas emission causes difficulties at measuring, methane emission process out of loose coal at К is suggested to be described as follows:

$$Q_К = \begin{cases} k_К m\, r\, \Delta L\, J_К (t\rho)^{-1} \exp((t_0 - t) / T_3), & t > t_0; \\ 0, & t < t_0, \end{cases} \qquad (10)$$

where $k_К$ – coefficient of methane transfer from the surface of loose coal at К, $1 = k_{УП} + k_К$; t – loosened piece of coal transportation in the longwall face by К, s; t_0 – the moment of loose piece of coal loading on К, s.

Thus, in order to determine gas emission out of loose coal at the conveyor it is necessary to know coal properties ($k_К$, ρ, m, T_3), characteristics and parameters of ОК operation (r, $v_{ОК}^{П}$) and К ($S_К$, ψ, φ) and shearer control law $v_К = f(v_{ОК}^{П})$.

Application area. Formulae (2)–(10) are the basis for the construction of the coal production process simulation model [16] in the problem of a mining machine optimal control system synthesis.

Conclusions. The suggested model of coal production process allows fully considering coal production process and taking it into account with limitations and suppositions, connecting stoping area aerogasdynamics, technological equipment operation, and coal bed behavior.

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СТРУКТУРНАЯ ИДЕНТИФИКАЦИЯ ОБЪЕКТА УПРАВЛЕНИЯ В ЗАДАЧЕ ОПТИМАЛЬНОГО УПРАВЛЕНИЯ ДОБЫЧНЫМ УЧАСТКОМ

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Введение. Основным путем обеспечения высокой рентабельности добычи угля является концентрация и интенсификация горных работ. Метаноносность угольного пласта, прогрессивные технологические схемы добычи, высокопроизводительная очистная техника приводят к росту метанообильности очистных выработок, загазированиям, простоям и значительным экономическим потерям.
Методика проведения исследований. Данное противоречие может быть разрешено путем оптимального управления добычным участком, которое предусматривает одновременное обеспечение высокой производительности и аэрологической безопасности. С использованием известных описаний аэрологических, технологических и геогазодинамических процессов разработана структура имитационной модели процесса добычи угля. Движение газовой смеси и выделение метана из раз-

личных источников в лаве предложено описывать в дискретном времени и пространстве. Осуществлен анализ влияния источников газа в общем газовоздушном потоке. Рассмотрен процесс формирования флюидного потока в угольном пласте и оценена возможность детального описания процесса десорбции газов.
Результаты. Проанализированы варианты моделей газовыделения из угольного пласта и из отбитого угля и движения газовоздушной струи в лаве и предложены адекватные, по мнению автора, структуры моделей. Выявлена взаимосвязь выделений метана из различных источников с режимами работы технологического оборудования. В результате определено достаточное количество переменных и сформирована параметрическая имитационная модель процесса добычи угля для разработки системы оптимального управления добычной горной машиной.
Ключевые слова: очистной участок; газовыделение; метан; идентификация; модель.

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