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MINERAL RESOURCES EXPLOITATION

Research paper

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Measurement of feeder performance during coal discharge from an underroof seam using machine vision

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Abstract

The technology for extracting and discharging coal from an underroof seam uses the so-called gravitational extraction method in which coal is extracted and discharged from under the roof by gravity. Here, coal can be discharged onto the main conveyor (face conveyor, located in the supported area), central conveyor (rear conveyor in Western literature), and tail conveyor (discharge conveyor, located in the unsupported area). The most common facilities used currently are longwall sets of equipment providing discharge onto tail conveyors. The purpose of this study is to measure the performance of a motorised plate feeder supplying coal from the outlet port of a roof support to a conveyor during the extraction of thick seams with discharge onto the face conveyor. To achieve the goal, it is proposed to measure the coal volume using machine vision. Methods for calculating a unit volume in a measuring section using a three-dimensional model were investigated. Laboratory studies were carried out to estimate the relative errors of the methods. The research allowed properly defining: a method for collecting data to calculate the unit volume of coal; a method for calculating the unit volume in the measuring section; a method for calculating the feeder performance using machine vision, and approaches for physically simplifying the video scene examined by machine vision. A relative error of less than 10 % with the existing measurement accuracy for constructing a coal layer surface height map indicates the sufficiency of the proposed calculation method for engineering use. The developed mathematical apparatus for calculating the unit volume of coal at the measuring section and measuring the feeder performance allows creating algorithmic software using the elementary mathematical functions of addition, subtraction, multiplication, and division. This aspect is important because it lower sights for the software development environment, and therefore expands the range of hardware suitable for calculating the feeder performance.

Keywords

mining, coal mining, coalface, performance, coal discharge, face conveyor, rock mass volume, machine vision, pattern recognition, video image recognition, height map

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РАЗРАБОТКА МЕСТОРОЖДЕНИЙ ПОЛЕЗНЫХ ИСКОПАЕМЫХ

Научная статья

Измерение производительности питателя при выпуске угля из подкровельной толщи на основе технологии машинного зрения

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Аннотация

Технология выпуска угля из подкровельной пачки использует так называемый гравитационный выпуск, когда уголь выпускается из-под кровли «самотеком» под действием силы тяжести. Выпуск при этом можно производить на главный конвейер (забойный – расположенный в закрепленном пространстве), центральный (в западной литературе – задний) и хвостовой (завальный – расположенный в незакрепленном пространстве). Наиболее распространенными на данный момент времени являются комплексы с выпуском на завальный конвейер. Целью исследования является измерение производительности механизированного пластинчатого питателя, подающего уголь от выпускного окна крепи на конвейер в технологии отработки мощных пластов с выпуском на забойный конвейер. Для достижения цели предлагается осуществлять измерение объема с применением технологии машинного зрения. Исследованы способы расчета единичного объема на измерительном участке на трехмерной модели. Проведены лабораторные исследования, в рамках которых оценены относительные погрешности.

Исследования позволили формализовать: способ сбора данных для расчета единичного объема угля; методику расчета единичного объема на измерительном участке; способ расчета производительности питателя на основе системы машинного зрения, а также подходы для физического упрощения сцены, исследуемой машинным зрением. Относительная погрешность менее 10 % при имеющейся точности измерений для построения карты высот говорит о достаточности для инженерного использования предложенного способа расчета. Разработанный математический аппарат для расчетов единичного объема угля на измерительном участке и измерения производительности питателя позволяют создавать алгоритмическое обеспечение с использованием элементарных математических функций: сложение, вычитание, умножение и деление. Данный аспект важен, так как снижает планку требований к среде разработки программного обеспечения, а соответственно, расширяет номенклатуру аппаратных средств, пригодных для выполнения задач расчета производительности питателя.

Ключевые слова

горное дело, добыча угля, лавный комплекс, производительность, выпуск угля, забойный конвейер, объем горной массы, машинное зрение, распознавание образов, распознавание видеоизображений, карта высот

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Introduction

The technology for extracting and discharging coal from an under-roof seam uses the so-called gravitational extraction method in which coal is extracted from under the roof by gravity. In this case, coal can be discharged onto a main conveyor (face conveyor, located in the supported area), central conveyor (rear conveyor in Western literature), and tail conveyor (discharge conveyor, located in the unsupported area) [3]. The most common systems currently are longwall sets of equipment with discharge onto the tail conveyor [4–7].

In the Russian Federation, an approach has been proposed for implementing controlled coal discharge by moving the rock mass flow using a motorised feeder from the outlet post to the main conveyor [8, 9]. Its main advantages include the small dimensions of the support section that are comparable to the dimensions of a classical longwall equipment set, as well as the ability to perform simultaneous group discharge from several sections, implementing promising coal mining technologies using wave and areal discharge [8, 9]. Implementation of such complex technological processes as wave and areal discharge requires developing a system for real-time monitoring of the volume of coal supplied by the feeder from the support outlet port to the main conveyor [9–12]. During group discharge, exceeding the calculated (design) coal supply volume from one feeder can overload the conveyor at the unloading points of the downstream feeders and coal spillage.

Discrete-event models were used to calculate the optimal coal discharge volume for each support section, sequence, and rational number of operating feeders, thus ensuring a steady discharge and maximum conveyor loading, at the FRC CCC SB RAS [13–15]. However, mining equipment capable of effectively measuring the volume of coal produced by a plate feeder under given conditions is not available on the market.

In world practice, solutions that use coherent light sources (laser emitters) to illuminate bulk solids to determine their volumes are known. Among the widely-used applications of such devices are machine vision conveyor performance meters [16–19], which use triangulation to create an array of values characterising the height of the layer of a substance moved by a conveyor at the point where it is intersected by a laser beam. However, this method allows measuring only the volume of bulk material moving through the scanner at a constant speed. There is equipment that uses 3D laser scanners (three-dimensional LIDAR) to determine the volumes of bulk solids moving at different speeds or in a static state [20, 21]. However, the issue of applying the technology in coal mines is poorly developed, with rare exceptions, such as the Australian project ExScan, which has not yet reached the stage of commercial sales and is a one-of-a-kind experimental product [22].

The analysis showed that there has been a significant number of studies published related to machine-vision-based laser volume estimation. However, no specific approaches to measuring the volume of rock mass moved by a feeder during the discharge of underroof coal seam have been identified. The problem of overloading in modern longwall sets of equipment with gravity discharge is solved by a small number of synchronised discharge sections numbering 1 to 5. In this case, an additional conveyor is used that minimises the risk of overload. In addition, the location of the conveyor in an unsupported area makes the effects of overloading less dangerous than when discharging coal onto the main conveyor, but may lead to increased coal losses. To date, automated devices do not record the presence of coal during coal discharge. In the approach described in [3], the outlet port flap opens for a given period of time and then closes without feedback or consideration of the successfulness of the coal discharge. The presence of the discharged coal is recorded visually in the reloader area. The main problem in measuring a plate feeder's performance is the lack of constant coal flow, since the plate feeder performs a reciprocating motion at a frequency close to 1 Hz. This type of feeder moves coal discretely in small batches with a sampling rate equal to the feeder frequency. The design and method of operation of this type of feeder does not allow using standard methods to measure performance by weighing or scanning the flow shape on the conveyors.

For experimental development, the task of measuring the volume of coal supplied by each feeder to the conveyor was divided into several subtasks:

1. Developing a method for calculating the performance based on the data on unit volume and its replacement rate.

2. Selecting the mathematical apparatus for calculating the unit volume of coal located in the measuring section.

3. Developing a methodology for primary verification and validation of the calculation of the coal unit volume in the measuring section.

4. Conducting primary verification and validation of the calculation of the coal unit volume in the measuring section.

5. Analysing the results of the primary verification and validation on the basis of which an algorithm for obtaining the calculation data by the machine vision system is chosen.

Research Methods

Initially, the measurement point along the area of coal reloading by the feeder from the inlet port to the conveyor was determined. The operation of the feeder in reciprocating motion can change the order of distribution of the discharged rock mass as it moves at any point along almost the entire path of coal transportation from the inlet port to the conveyor. The only transportation section where the coal mass movement direction and substitution rate is constant is the outlet channel. The outlet channel is a hinged element mounted on the feeder through which coal passes from the feeder to the conveyor via the process opening between it and the support section. A feasible method for calculating the feeder performance is by first calculating the volume of coal in a given section of the feeder channel (measuring section), then determining the time it takes to replace this section with a new portion of coal. The mathematical apparatus for calculating the feeder performance in this case is reduced to calculating the volume of the body representing the volume of the coal mass in the measuring section per unit time:

$$P_{feed} = V_{unit} \cdot T_{repl}, \quad (1)$$

where P_{feed} is feeder performance, m^3/s; V_{unit} is the unit volume of coal in the measuring section, m^3; T_{repl} is the replacement frequency of coal portions in the measuring section, s^{-1}, directly proportional to the frequency of the feeder and coming into the calculation formula from the automation devices of the longwall set of equipment.

On this basis, the input data for calculating the volume of coal in the measuring section are set. Correspondingly, to measure the volume of the discharged coal per unit time, its volume and replacement rate are measured at the measuring section. The optimal performance of the feeder according to the discrete-event discharge model [13] is calculated in kilograms per second. Thus, using the coal bulk density, the performance is calculated as

$$P_{feed(kg/)} = \rho_{coal} \cdot V_{unit} \cdot i_{repl}, \quad (2)$$

where ρ_{coal} is the bulk density of coal at the section of the extracted seam.

The replacement rate is a value that is determined using data obtained at the pre-commissioning stage and depends on the size fraction of coal discharged and the feeder frequency. When measuring the volume, the shape of the measuring section is taken to be rectangular. The measured coal mass in the measurement area has a variable height over its entire area. To calculate the coal volume, data characterising its height relative to the level of the measuring section at given points is required.

The most obvious option for obtaining the dataset required for the mathematical apparatus is a machine vision system combined with a neural network interface for pattern recognition [13, 14]. However, for the correct operation of a pattern-recognising neural network, a significant training set is typically required that will not be available until the pilot commissioning of a longwall set of equipment of an appropriate design. Besides, the low image quality obtained from modern video cameras certified for installation in longwall sets of equipment limits the applicability of classical algorithms of video scene recognition. This clearly demonstrates the relevance and need to simplify the analysed video scene prior to its computer processing.

To solve this problem, it was proposed to project a rectangular grid of laser beams of contrasting colour (hereinafter referred to as light markers) onto the studied surface. The light markers will provide a projection onto an uneven surface and will change their shape from being straight to the shape of the area on which they are projected, which will provide information about the shape of the area under the light markers. The next step is determining the light marker coordinates relative to the level of the measuring section at any of its points in manual mode without using neural network video recognition techniques.

The presence of a light marker greatly simplifies the recognition of a video scene by machine vision, creating in the scene picture a clear contrasting area in terms of illumination and colour relative to other objects. This area is processed by eliminating unnecessary information from the image at the preprocessing stage. This approach will determine the pattern recognition algorithms, reducing the computer power requirements of the device on which the video signal is processed.

Research Findings

To calculate the volume of coal in the measuring section, the coal layer height was measured only at the points of the layer intersection with light markers, thus forming a map of heights of the coal layer in the measuring section.

We will represent the measuring section as a set of parallelograms with equal bases and heights, corresponding to the data from the height map. The sum of the volumes of the obtained parallelograms will be the volume of the figure in the studied section.

Primary verification of the proposed method is performed using a reference geometrical figure with a curved surface (a hemisphere), the volume of which can be pre-calculated by the formula by setting the overall dimensions comparable to the size of the measuring section with the actual feeder. The expected volume of the hemisphere V_{exp} was calculated by formula (1) and amounted to $261.8 \cdot 10^6$ mm^3:

$$V_{exp} = \frac{\frac{4}{3}\pi r^3}{2}. \tag{3}$$

Input data: radius r, mm, 500; light marker grid pitch along the X axis, mm, X = 50 (constant); light marker grid pitch along the Y axis, mm, Y = 50 (constant); point coordinate along the X axis, x_i; point coordinate along the Y axis, y_n; layer height, mm, at point with coordinates $h_{x,y}$.

Thus, the reference figure with the volume calculated using the proposed method has a circle with a radius of 500 mm at its base. The measurement area is represented by a 1,000 × 1,000 mm square simulating the measuring section on the feeder surface. The reference figure is inscribed in the measurement area. The light markers are represented by vertical and horizontal sections in the measurement area at 50 mm increments in both directions.

To collect the data, it was proposed to perform a conditional dissection of the reference figure at the places where the light markers pass to obtain a set of small figures. Thus, the small figure is a volumetric body with two equal parallel side surfaces that are curvilinear trapezia obtained by dissecting the hemisphere at the h_y coordinate. The volume of the small figure V_1 can be calculated by the formula:

$$V_1 = S_{ss} \cdot Y, \tag{4}$$

Where S_{ss} is the side surface area; Y is the dimension of the small figure along the Y axis. The area of the curvilinear trapezium is calculated using a definite curvilinear integral. High accuracy is not required when calculating the feeder performance; the calculated volume is negligible relative to the total second performance. However, the calculation speeds are important. The heights of the rectangles h_x in increments of X are entered into the table for the calculations. The resulting table is a map of heights for calculating the volume of a small figure. Then S_{ss} can be calculated by the following formula:

$$S_{ss} = X\sum_{x=1}^{x_2} h_x; \tag{5}$$

correspondingly,

$$V_1 = YX\sum_{x=1}^{x_2} h_x. \tag{6}$$

Consequently, the volume of the whole reference figure V_{calc} is represented as a sum of the volumes of all rectangular parallelepipeds included in all small figures into which the reference figure was divided. Then, V_{calc} is calculated by the formula:

$$V_{calc} = XY\sum_{y=1}^{y_2}\sum_{x=1}^{x_2} h_{x,y}, \tag{7}$$

where

$$\sum_{y=1}^{y_2}\sum_{x=1}^{x_2} h_{x,y}$$

is the sum of all heights measured in the sample sections with coordinates $h_{x,y}$.

The reference figure was built using the CAD modeling system Free CAD. The resulting volumetric model of the hemisphere was sequentially dissected along the *X axis* in increments specified in the condition, after which a curvilinear surface height map was created in each resulting section, representing a small figure. The heights were measured in increments of X. The process of sequentially obtaining the height coordinates as data to form the height map is shown in Fig. 1.

Further, the height data are entered into the table, the general view of which is shown in Fig. 2.

The resulting height map simulates the information from the machine vision system. To control the reliability of the measurement results, the surface diagram based on the table data was built, see Fig. 3, *a*.

The surface diagram built using MS Excel shows that the measurements during the construction of the height map were made with no gross errors and can be used for primary verification of the volume calculation method.

As can be seen from Fig. 1, the sections Y form small bodies with flat sides and a base bounded from above by a curvilinear surface that corresponds to the proposed calculation method. Thus, the whole reference figure is represented as a set of corresponding rectangular parallelepipeds having a base of size X by Y. Fig. 3, *b* presents an image of a simplified reference body obtained by converting all small bodies into rectangular parallelepipeds.

The volume of the reference figure calculated by formula (7) was $259.3 \cdot 10^6$ mm^3. The measurement relative error is 0.95 % of the expected result.

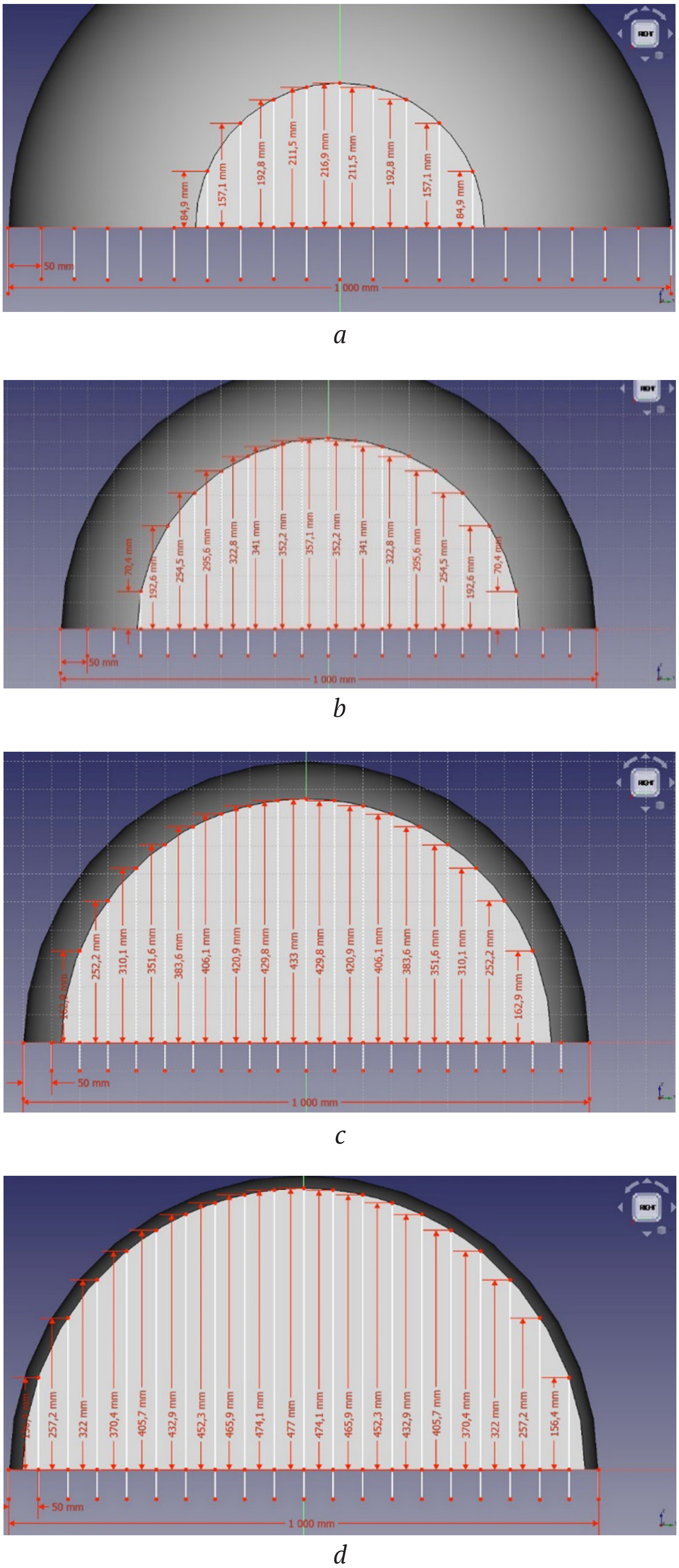
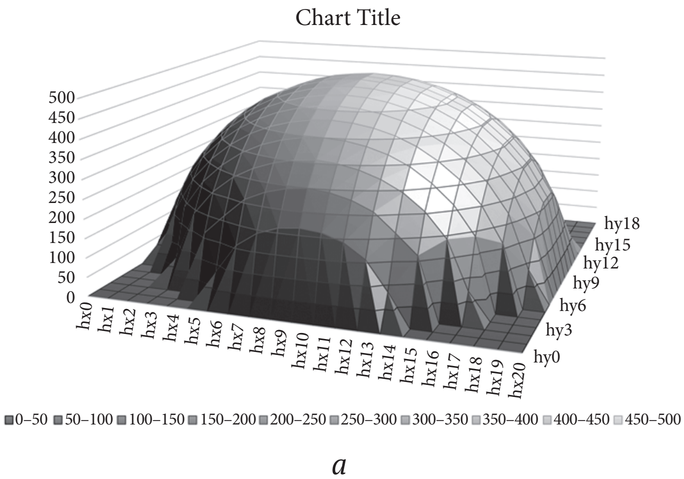


Fig. 1. The process of obtaining the coordinates of the rectangles vertices by section: For height map building: *a* – section 2; *b* – section 4; *c* – section 6; *d* – section 8

Height coordinates	h_x	h_{x+1}	...	h_{x+i}
h_y	$h_{x,y}$	$h_{x+1,y}$	...	$h_{x+i,y}$
h_{y+1}	$h_{x,y+1}$	$h_{x+1,y+1}$	...	$h_{x+i,y+1}$
...	...	...	...	...
h_{y+n}	$h_{x,y+n}$	$h_{x+1,y+n}$	...	$h_{x+i,y+n}$

Fig. 2. General view of the height map data table:
$h_{x,y}$ is the height from the zero mark with coordinates x, y to the curve limiting the surface of the section at the dissection location



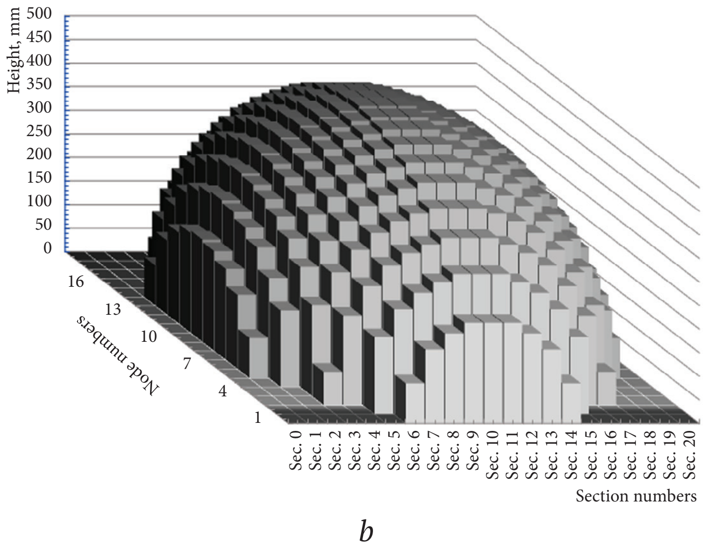


Fig. 3. Representation of the reference figure:
a – in the form of a surface diagram based on measurement data; *b* – obtained by the rectangle method based on measurements

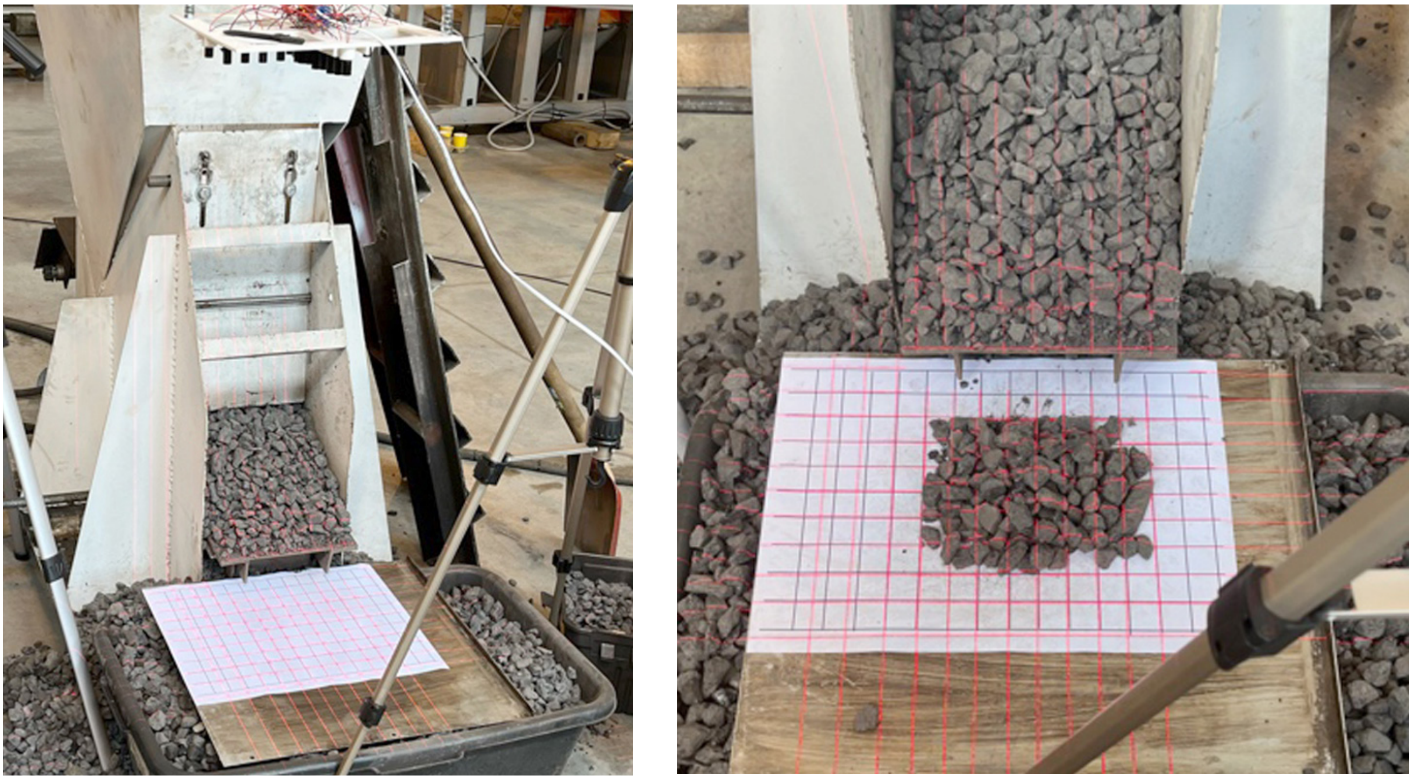


Fig. 4. Technique validation process using a measuring section model

To validate the technique, a series of laboratory experiments were carried out using laser grid projection tools on a flat surface (measuring section) simulating the support section feeder outlet channel. In the experiments, a known volume of coal (Fig. 4) with pre-measured bulk density and weight was placed at the measuring section that enabled mathematical calculating its volume.

To construct the height map, the layer of coal used was probed with a wire spoke in the locations of its intersection with laser beams, then the coal level was fixed on the spoke with a marker. The measurement data was used to build the height map presented in Table 1, where y is the coordinate of the measuring point in the cross section of the measuring section with the reference point on the feeder side and x is the coordinate of the measuring point in the longitudinal section of the measuring section with the reference point in the leftmost part of the coordinate grid.

Table 1

Map of coal layer heights at the measuring section, mm

$h_{x,y}$	x_1	x_2	x_3	x_4	x_5	x_6	x_7	x_8
y_1	10	27	8	5	16	16	0	0
y_2	14	23	11	27	15	26	23	0
y_3	20	25	35	34	40	13	35	17
y_4	18	19	34	43	32	29	27	12
y_5	25	20	30	25	26	21	20	0
y_6	20	5	12	26	28	21	13	0
y_7	0	0	17	13	10	8	24	0

Based on the bulk density of coal and the weight of the sample, the expected volume $V_{exp} = 0{,}74 \cdot 10^6$ mm^3 was calculated.

The size of the light marker grid cells $h_x = 25$ mm, $h_y = 25$ mm.

The calculated volume $V_{calc} = 0{,}63 \cdot 10^6$ mm^3 is determined by formula (5).

The relative error of V_{calc} (the difference with V_{exp}) was 13.55 %.

The resulting relative error is quite large due to two factors. The first is the imperfect measurement methods used, and the second factor is the simplification of the methodology for calculating the volume, poorly taking into account the heterogeneity of the surface of the coal volume and its distribution over the measuring section.

To compensate the heterogeneity of the measured coal volume surface in the calculation, calculation by the rectangle method with double recalculation in opposite directions and subsequent averaging of the result was proposed:

$$V_{calc1} = \frac{\left(\sum_{y=1}^{y_2-1} \sum_{x=1}^{x_2} h_{x,y} + \sum_{x=1}^{x_2} h_{x,y_2-1} + \sum_{y=2}^{y_2} \sum_{x=1}^{x_2} h_{x,y} + \sum_{x=1}^{x_2} h_{x,2} \right) YX}{2}. \quad (8)$$

Applying formula (8) to the data from Table allows determining $V_{calc1} = 0{,}67 \cdot 10^6$ mm^3.

The relative error of V_{calc1} (the difference with V_{exp}) was 8.87 %.

Discussion

The method used in the experiment to build a coal layer height map has an error because a bulk material (coal) of varying grain size is used; correspondingly, the material particles shift in the course of the measurements. Despite this, the above approach demonstrates acceptable accuracy in the direct calculation of the volume with a relative error of less than 14 %. Using the measurements with passage in two opposite directions relative to the cross section of the measuring section with subsequent averaging of the measurement data allows reducing the relative error for this case by almost 5 %. The 5 % error is a variable value and depends on the distribution of the coal volume relative to the cross section of the measuring section. The relative error of less than 10 % with the available accuracy of the measurements for constructing a height map proves the sufficient accuracy of the proposed calculation method for engineering use and the small influence of the errors of individual measurements on the overall volume calculation result.

Based on the validation results, a formula for calculating the feeder performance, P_{feed}, kg/s, can be obtained by substituting (8) into (2). Then:

$$P_{feed} = \frac{\left(\sum_{y=1}^{y_2-1} \sum_{x=1}^{x_2} h_{x,y} + \sum_{x=1}^{x_2} h_{x,y_2-1} + \sum_{y=2}^{y_2} \sum_{x=1}^{x_2} h_{x,y} + \sum_{x=1}^{x_2} h_{x,2} \right) YX}{2} \rho_{coal} T_{repl}. \quad (9)$$

The resulting formula (9) allowed initiating the development of machine vision software, measuring the height of the coal layer at the points of its intersection with light markers.

Conclusion

The proposed method allows for a rapid assessment of the volume of rock mass moved by a plate feeder using machine vision. The problem of controlling the volume of coal discharged by the feeder when extracting thick seams using longwall sets of equipment with coal discharge to the face conveyor having an accuracy sufficient for practical application was solved. The developed mathematical apparatus for calculating the unit volume of coal at the measuring section (formula (8)) and measuring the feeder performance (formula (9)) allows creating algorithmic software using the elementary mathematical functions of addition, subtraction, multiplication, and division. This aspect is important because it lower sights for the software development environment, and therefore expands the range of hardware suitable for calculating the feeder performance.

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New methods of predicting and prospecting/exploration of hydrocarbon deposits to improve exploration performance in the Timan-Pechora oil and gas province

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Abstract
The Timan-Pechora oil and gas province remains rather promising for the discovery of new hydrocarbon fields and deposits, including large ones. However, in recent years, the efficiency of oil and gas prospecting and exploration has been rather low. At relatively high exploration maturity of prognostic oil resources (> 50%) and low exploration maturity of gas resources (about 30%), prospecting for new fields and deposits focuses on non-standard geological conditions of their occurrence. This, in turn, requires the development of new methods and technologies for the development of such resources and the simulation of hydrocarbon systems and specific deposits, reflecting their non-standard occurrence and structure, thereby making prospecting more complicated. Therefore, the determination of rational methodological approaches to prediction, prospecting, and exploration of hydrocarbon deposits represents an urgent scientific and applied task.
A comprehensive analysis of geological and geophysical characteristics of the promising targets based on the data of up-to-date seismic exploration and drilling ensures that complex traps are mapped by geophysical methods and prognostic resources and reserves of discovered deposits are estimated more precisely and confidently. Integration and analysis of geological and geophysical research materials using advanced methods and technologies can significantly expand oil and gas prospects and optimize the prospecting for productive traps and increase exploration efficiency by reducing the risk of unproductive wells.
This paper presents and discusses the options for predicting oil and gas potential and provides recommendations for prospecting hydrocarbon deposits using up-to-date methods and technologies for interpreting geological and geophysical data. The research targets were terrigenous and carbonate natural reservoirs in the northeastern part of the Timan-Pechora oil and gas province, including the shelf of the Pechora Sea, Izhma-Pechora and Khoreiver Basins situated in different structural and tectonic zones. The analysis of extensive geological information has revealed that these areas exhibit all the necessary conditions for the existence of unique geological features and the potential for the discovery of oil and gas deposits therein.

Keywords
Timan-Pechora oil and gas province, hydrocarbon deposit, resources, reservoir, impermeable bed, seismic exploration, well

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ГЕОЛОГИЯ МЕСТОРОЖДЕНИЙ ПОЛЕЗНЫХ ИСКОПАЕМЫХ

Обзорная статья

Новые технологии прогноза и поисков залежей углеводородов с целью повышения эффективности геологоразведочных работ в Тимано-Печорской нефтегазоносной провинции

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Аннотация

Тимано-Печорская нефтегазоносная провинция остается достаточно перспективной для открытия новых месторождений и залежей углеводородов, в том числе крупных. В то же время в последние годы отмечается низкая эффективность поисково-разведочных работ на нефть и газ. При относительно высокой разведанности прогнозных ресурсов по нефти (> 50 %) и невысокой по газу (около 30 %) поиск новых месторождений и залежей смещается в сторону нестандартных геологических условий их залегания. Это, в свою очередь, требует разработки новых методик и технологий освоения таких ресурсов, построения моделей углеводородных систем и конкретных залежей, отражающих нестандартные условия их залегания и строения, а также усложнение поискового процесса. Поэтому определение рациональных методических подходов к прогнозированию, поискам и разведке залежей углеводородов представляет собой актуальную научную и прикладную задачу.

Комплексный анализ геолого-геофизических характеристик объектов по материалам современной сейсморазведки и бурения обеспечивает картирование геофизическими методами сложнопостроенных ловушек и более точную оценку прогнозируемых ресурсов и запасов обнаруженных залежей. Комплексирование и анализ материалов геолого-геофизических исследований с применением прогрессивных методик и технологий позволяют значительно расширить нефтегазовые перспективы, оптимизировать процессы поисков продуктивных ловушек и повысить эффективность геологоразведочных работ за счет рисков снижения непродуктивных скважин.

В статье авторы рассмотрели варианты прогноза нефтегазоносности и дали рекомендации поисков залежей углеводородов с применением современных методов и технологий интерпретации геолого-геофизических данных. Объектами исследований являлись терригенные и карбонатные природные резервуары северо-восточной части Тимано-Печорской нефтегазоносной провинции, включая шельф Печорского моря, Ижма-Печорской и Хорейверской впадин, расположенных в разных структурно-тектонических зонах. Анализ обширной геологической информации показал, что на этих площадях есть все необходимые условия существования уникальных геологических объектов и возможность открытия в них нефтегазовых залежей.

Ключевые слова

Тимано-Печорская нефтегазоносная провинция, залежь углеводородов, ресурсы, коллектор, флюидоупор, сейсморазведка, скважина

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Introduction

The Timan-Pechora oil and gas province exhibits an unique complexity and diversity of geological features as well as the conditions of their formation. Within the province, the potential for oil and gas is observed almost everywhere and throughout the entire sedimentary sequence, from Ordovician to Mesozoic sediments inclusive.

The main areas of exploration for new deposits here currently include:

a) **for oil**:

– Middle Ordovician-Lower Devonian oil-gas play with an extensive development of non-anticlinal, structural-stratigraphic, lithological, erosion traps within the Bolshezemelsky paleo-dome, Denisovsky trough, the Pechora Sea shelf;

– Permian-Triassic terrigenous oil-gas play with an extensive development of lithological traps of deltaic genesis within the northern part of the Timan-Pechora Province and its Arctic extension;

– The Visean-Lower Permian oil-gas play with bioherm, reefogenic and biostromal traps throughout the Timan-Pechora Province and its Arctic extension;

b) **for gas**:

– the main target is the Pre-Ural foredeep with the widespread development of large structural-tectonic traps in the central and internal zones of the foredeep;

– myogeosynclinal zones hidden under the Ural frontal folds may be a new non-traditional lines [1].

These are the key lines of the research described in this paper. Based on three examples, the authors demonstrated an algorithm for predicting and prospecting hydrocarbon deposits using modern methods and technologies for interpreting geological and geophysical data.

We have analyzed and interpreted more than 200 wells, 30,000 linear km of seismic exploration using the Common Depth Point (CDP) Method (2D), 900 km^2, 3D.

The used data processing and corresponding graphs were performed applying up-to-date geological, mathematical and graphical software packages: Kingdom Suite (SMT), Petrel (Shlumberger), IESX (Shlumberger Sparc GeoFrame), Paradigm Geophysical (Probe and Vanguard), Excel, CorelDRAW.

Research Findings

Example 1. The use of the historicalandgenetic method for predicting traps and hydrocarbon deposits

The assessment of the prospects of oil and gas potential of a territory on the basis of the historicalandgenetic method underlies almost all methods of predicting the oil and gas potential of the subsoil and is broadly used both in the Russian Federation and in foreign countries. Such well-known scientists as A.P. Afanasenkov, L.I. Bogorodsky, L.N. Boldushevsky, I.P. Varlamov, G.D. Ginzburg, A.I. Danyushevsky, S.V. Yershov, N.S. Kim, A.E. Kontorovich V.A. Kontorovich, Robert Lowkes, John Dolsen, Stefan M. Luti et al. The use of the historicalandgenetic method contributed significantly to the discovery and development of such deposits as Zapolyarnoye, Urengoy, Medvezhye, Yamburgskoye, Messoyakhskoye, Solyoninskoye, Yuzhno-Solyoninskoye, Pelyatkinskoye, Ushakovskoye, Deryabinsky, Vankor Group, Giddings, Black Giant (East Texas), and other deposits in Texas, Louisiana and Mississippi [2–4].

In the paper, the authors, based on the study of various factors in the formation of traps and deposits, propose to consider a systematic scientific approach to the historicalandgenetic method for predicting traps and hydrocarbon deposits, which consists in the analysis of events that took place in Permian and Triassic periods that affected:

1) tectonic-dynamic development of the investigated area;

2) sedimentation processes;

3) generation and accumulation of hydrocarbons;

4) reformation of hydrocarbon deposits during the Permian period, and then during the Triassic and Jurassic periods.

The subject of the research. The northeastern part of the Timan-Pechora oil and gas province, terrigenous deposits of Permian age (Fig. 1).

Sedimentation originates from the main source of ablation of terrigenous material in the Early Artian time from the Ural Orogen. The development of orogenic processes in the Urals gave rise to extensive regression, then in each period of time up to the Kazanian-Tatarian time, sedimentation conditions changed.

Regionally, in the early Artian time, carbonate sedimentation was gradually replaced by terrigenous sedimentation, and coastal marine conditions with carbonate-terrigenous sedimentation originated within the depressions of the Pre-Ural Foredeep; in the central part of the Varandey-Adzvinsky structuralandtectonic zone and the Kolvinsky megaswell, deep-water and shallow sea sediments were accumulated, and formation of organogenic structures took place. Deep-water sedimentation conditions occurred in the area of the present Korotaikhinskaya Basin. As terrigenous sedimentation developed over the investigated areas during the Permian period, a new sedimentation basin with coastal marine, deltaic, and alluvial sedimentation conditions formed [5].

At the zonal level, the sedimentation and post-sedimentation sub-stages of trap formation of coastal-marine, channel and deltaic origin in Artian-Kungurian and Ufian-Tatarian time are considered.

The Permian terrigenous sediments within the Korotaikhinskaya Basin are one of the main targets for prospecting for hydrocarbon deposits. The resulting oil inflow from these deposits in well 1-VK (Vorkutinskaya) indicates their high prospects.

In the investigated part of the Korotaikhinskaya Basin, time sections in the interval between the reflecting horizons (RH) I-II and A-I are characterized by a clinoform recording according to the wave pattern, which is identified with the formation of presumably deltaic Permian sediments (Fig. 2).

The Permian terrigenous clinoform complex constitutes a system of progradational clinoforms – cyclites that formed during the regressive phase of the Permian stage of the basin evolution, and is associated with the final orogenic stage of the Hercynian-Early Cimmerian cycle.

The clinoform complex was studied using six wells: 2-Zapadno-Korotaikhinskaya, 1-, 2-Reef, 1-Vorkutinskaya (VK), 1-Khavdeyskaya, 15-Labogeyskaya. Downhole information on them is incomplete, there are no data in the Perm part of the section: self potential (SP) in well 2-Zapadno-Korotaikhinskaya; acoustic logging (AK) – in wells 1-Khavdeyskaya, 1-VK; NGK – in wells 1-Khavdeyskaya, 1-VK. The quality of available materials for geophysical studies of wells was affected by the long research intervals and the long period of time from the moment the section was opened to the field geophysical survey research. The insufficient amount of core material also makes it difficult to conduct a facial-paleogeographic analysis of these sediments.

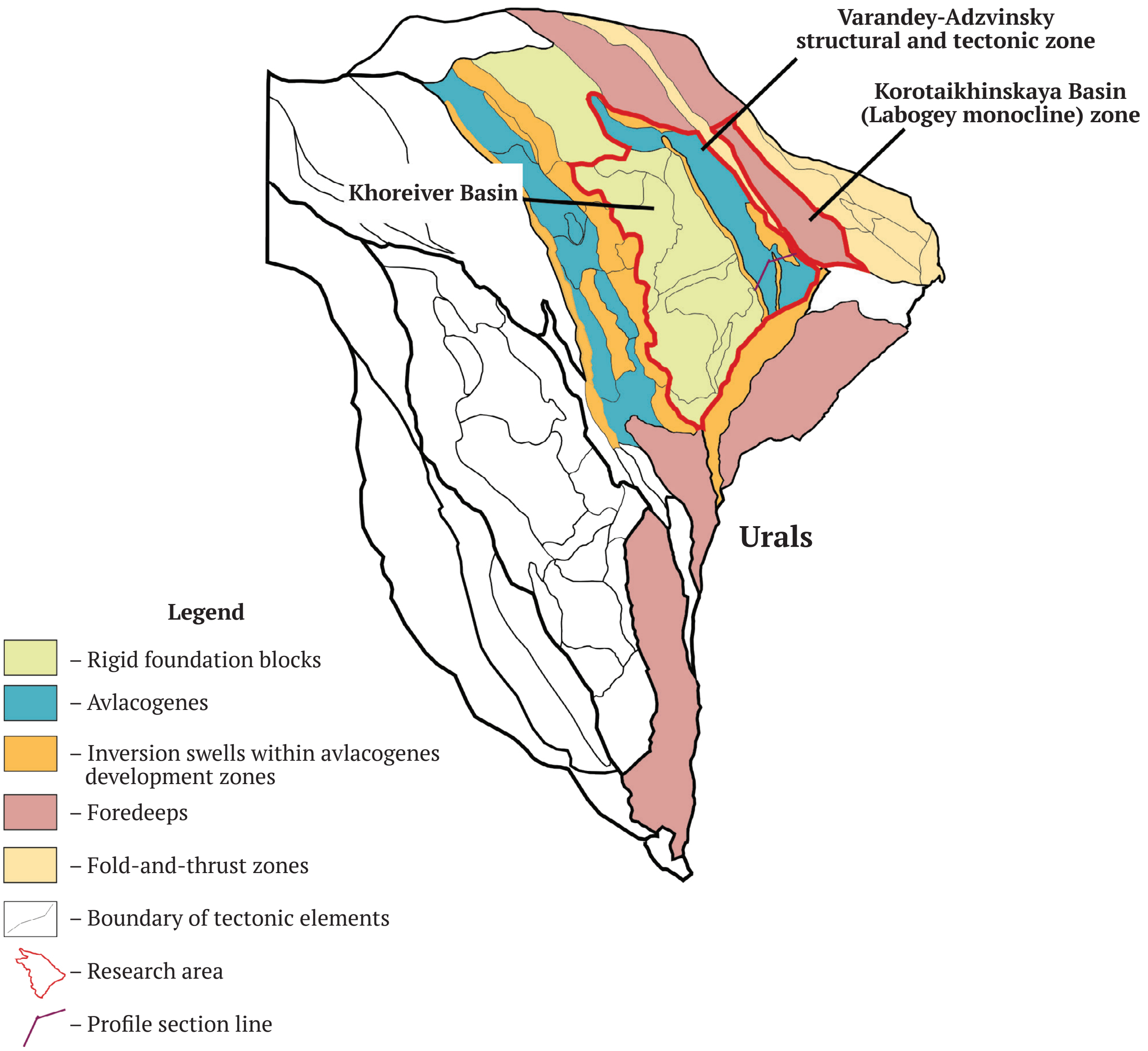

Fig. 1. An overview map of the investigated area (compiled by I. A. Marakova)

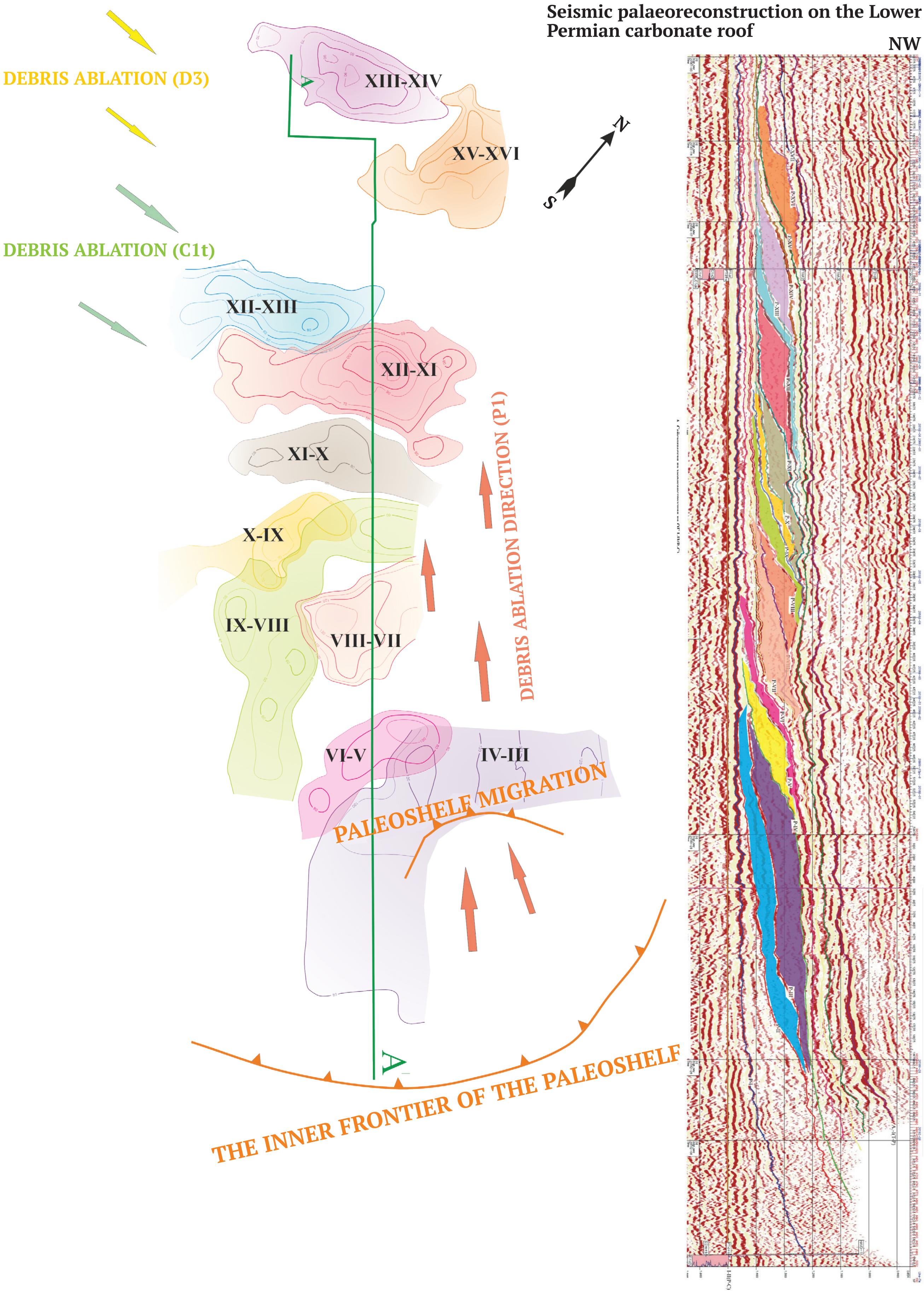

Fig. 2. Model for the formation of a progradational complex (based on materials from Severgeofizika)

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Since there are no equivalent deposits in Permian clinoform sediments in the Timan-Pechora oil and gas province, the methodology and prospecting criteria developed in the course of studying West Siberian clinoform sediments were used to identify promising targets in the Timan-Pechora province.

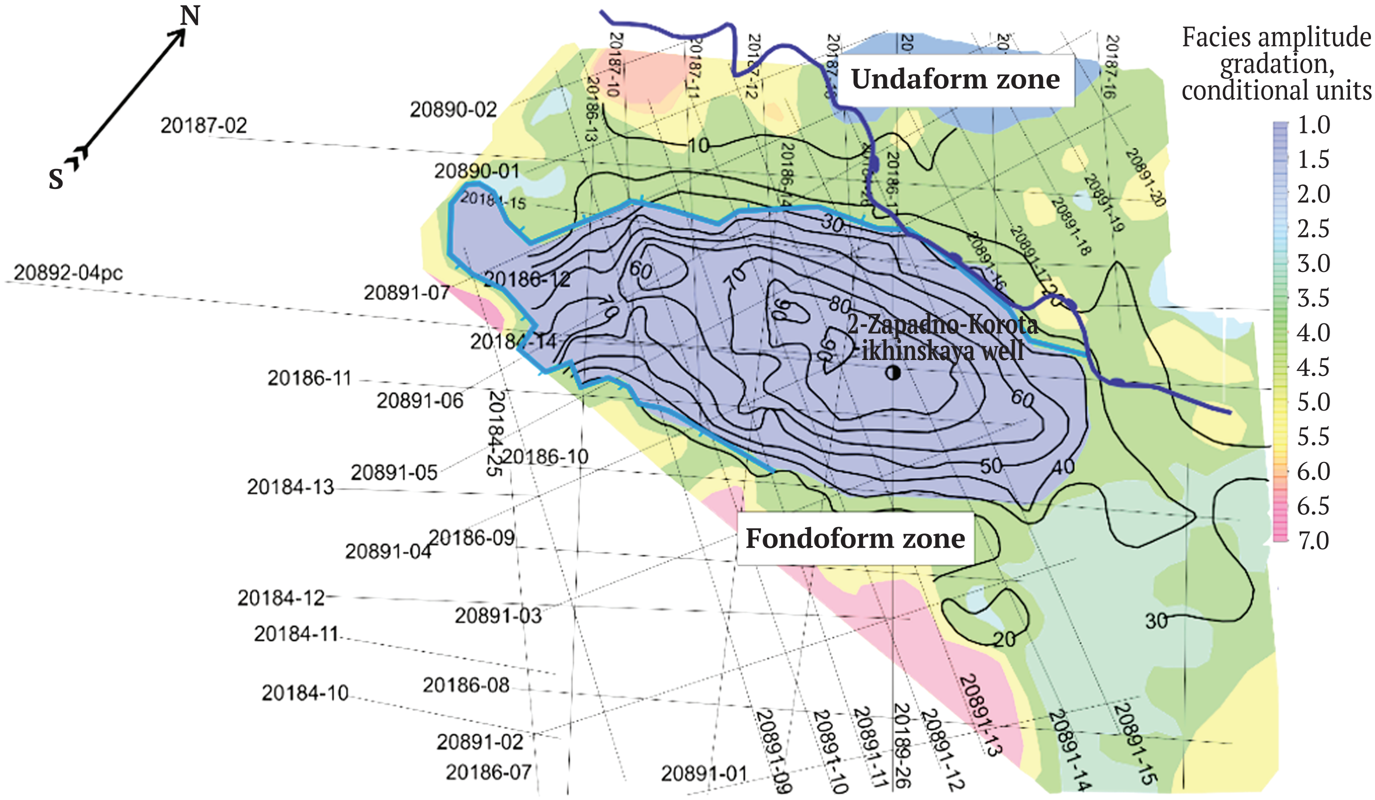
The clinoform complex is characterised by a complex structure, which is evident in the variability of reflections from profile to profile, the complex relationship between reflections in the shelf, slope, and foothills, as well as the variability of clinoforms along the strike, which is evident in the formation of locally developed zones of increased thicknesses, namely depocentres.

The presence of depocenters indicates the existence of a feeding canyon, through which the amount of sedimentary material introduced was more significant as compared to the periphery, and their configuration and extension suggest different intensities of the material processing and movement by currents along the slope.

Within the depocenter of the clinoform formed by the R-XIV and P-XIII reflecting boundaries, 2-Zapadno-Korotaikhinskaya well was drilled (Fig. 3). Core logging (interval 2,355.2–2,416.3 m) revealed the sequence primarily consists of interbedding of siltstone, dense strong and sandy mudstone with sandstone layers.

The P-XIV sigmoid seismic boundary surrounding this clinoform is expressed confidently and clearly. According to geophysical studies of wells, the roof of the sandstone stratum (2,323–2,334 m) is identified with this reflection. It is difficult to estimate the storage capacity and fluid content of the identified sandstone, since this interval is characterized by an incomplete range of geophysical logging, the absence of core and well tests.

Within this clinoform in the well, sandstone layers of low thickness (interval 2,362–2,376.4 m) saturated with bitumen-like viscous oil in sparse pores are observed.



Paleoslope base line

The boundary of the suggested lithological replacement (the strokes are directed towards the of clayey-aleuritic formations occurrence area)

Seismic profile line, pickets

40 Isolines of temporal thickness (ms) between reflecting boundaries P-XIII and P-XIV traced in the clinoform complex of Permian-age terrigenous sediments

Fig. 3. Map of seismic facies (based on the materials from Severgeofizika JSC)

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Based on the calculations of the Komi Scientific Center of the Ural Branch of the Russian Academy of Sciences [6] and VNIGRI (All-Russian Petroleum Research Geological Exploration Institute) [7], Table 1 presents the extent of hydrocarbon expulsion from the oil source horizons of the Timan-Pechora Sedimentation Basin (TPSB) and the distribution of liquid and gaseous hydrocarbon expulsion volumes by Permian age sediment in the Korotaikhinskaya Basin.

The extent of hydrocarbon expulsion in the Korotaikhinskaya Basin has been so enormous that, even with extremely low hydrocarbon retention rates, significant oil and gas resources are expected to persist. The oil and gas potential of the studied Permian sediments in the Korotaikhinskaya Basin is also confirmed by the results of the Basin modeling [8].

A large oil accumulation zone is predicted within the Labogey monocline, the Vashutkin-Talotinsky thrust, extending further into the Saremboy-Lekkeiagin zone in a stratigraphic range from the Upper Devonian to the Triassic. This is confirmed by numerous oil shows in Permianage sediments, bituminous saturation and brown oxidised oil admixture in cores from the Devonian and Permian intervals.

Conclusions (Findings). The results of dynamic analysis of the sigmoid seismic boundaries (seismic facies maps) enveloping the clinoforms have identified three possible lithologically constrained traps, one of which is located in the fondoform subzone, the second is in the shelf and clinoform subzone, and the third – in the shelf subzone.

To identify a lithologically constrained trap formed in the shelf and clinoform subzones, the data of the 2-Zapadno-Korotaikhinskaya well were used, in which a sandstone layer from the interval of 2,323–2,334 m was identified as P-X IV reflecting horizon. The dimensions of this trap are 24 × 10 km.

The third lithologically bounded trap in the shelf subzone was identified in a manner analogous to the trap identified using the R-XIV reflecting horizon.

To study the facial features as well as oil and gas potential of the clinoform seismic complex, three wells should be drilled. This profile of three wells will make it possible to obtain fundamentally new data on the structure of clinoforms and map, in the future, a zone of possibly oil-saturated reservoirs associated with the edge of the shelf and identified by logging in 2-Zapadno-Korotaikhinskaya well.

The recoverable resources within the investigated area in D1 category are estimated at 18,213 kt and raises the prospects of the investigated area by 30 %.

Example 2. Application of the CDP dynamic analysis findings in predicting reservoir occurrence zones in the poorly drilling-explored areas

Exploration targets. Areas located within the junction of the Varandey-Adzvinsky structural zone and the Khoreiver Basin (the northeastern part of the Pechora Sea shelf). 600 km2 of CMP-3D surveying was carried out at the survey sites (areas A and B), wells A-1 and B-1 were drilled, which penetrated into Lower Silurian and Carboniferous sediments, respectively.

Prospective sediments. Upper Permian terrigenous strata of the Kazanian-Tatarian Stage, Upper Carboniferous-Lower Permian carbonate strata of the Asselian-Sakmarian Stage and Silurian carbonate strata. The oil and gas content of these deposits has been proven at many fields of the Timan-Pechora oil and gas basin and is confirmed by the inflows of hydrocarbons from wells A-1 and B-1 in the investigated area.

Table 1

Extent of expulsion from the oilbearing horizons of the TPSB and distribution of the expulsion volumes of liquid and gaseous hydrocarbons in the Korotayikhinskaya Basin

Oil and gas source age	Extent of hydrocarbon expulsion		Expulsion density		Sediments					
	oil, billion tons	gas, trillion m³	oil, million tons/km²	gas, gas, trillion m³/km²	P_1ar		P_1k		P_1u	
					Oil, billion tons	Gas, trillion m³	Oil, billion tons	Gas, trillion m³	Oil, billion tons	Gas, trillion m³
$S_1 + S_2 + D_1$l	568.2	220.7	0.024–14.559	0.005–5.611						
D_2	167.3	66.4	0.013–3.256	0.011–1.309						
D_3tm-sr	109.2	44.4	0.016–1.850	0.014–0.713	4.8	52.24	3.25	37.88	2.9	24.96
D_3 Dm (sm)-C_1t	410.5	114.8	0.033–7.890	0.01–2.458						
P_1ar-k	172.4	124.5	0.004–7.092	0.008–8.982						
Σ	1427.6	570.8	–	–	4.8	52.24	3.25	37.88	2.9	24.96

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The following studies were carried out to assess the identified prospects for porosity & permeability in the reservoir zone and hydrocarbon content:

1. Comprehensive analysis of well data (geophysical well surveys, test results, sampling, drilling);
2. Review of petrophysical properties of rocks (finding correlations between attributes and petrophysical parameters);
3. Structural interpretation: correlation of reflective horizons, isolation of disjunctive dislocations, isochron mapping, identifying seismic recording anomalies;
4. Performing attribute analysis to predict zones of high-capacity reservoir development in the target intervals of the sequence [9, 10].

Changes in the petrophysical properties of rocks, their saturation nature and lithological composition are reflected both in the factual material (cores, cuttings, thin sections) and the curves of geophysical well survey data. Comprehensive analysis of well data (A-1, B-1) does not allow to confidently separate the reservoir and non-reservoir point cloud and identify reliable correlation relationships between elastic and petrophysical rock properties to propagate permeability and porosity in the inter-well space due to the limited set of geophysical well survey data.

Since this area is poorly explored by drilling, the changes in the pore volume of Upper Permian terrigenous deposits are additionally considered on the basis of the results of petroelastic modeling based on the Gassmann equations (Fig. 4). As a priori information, the average porosity ratios of the Kharyaga (K_p = 26%) and Lem'yusky (K_p = 21%) peer fields developed onshore were used. It has been established that when a reservoir with porosity of 21% is found, the reservoir and non-reservoir points keep overlapping: at

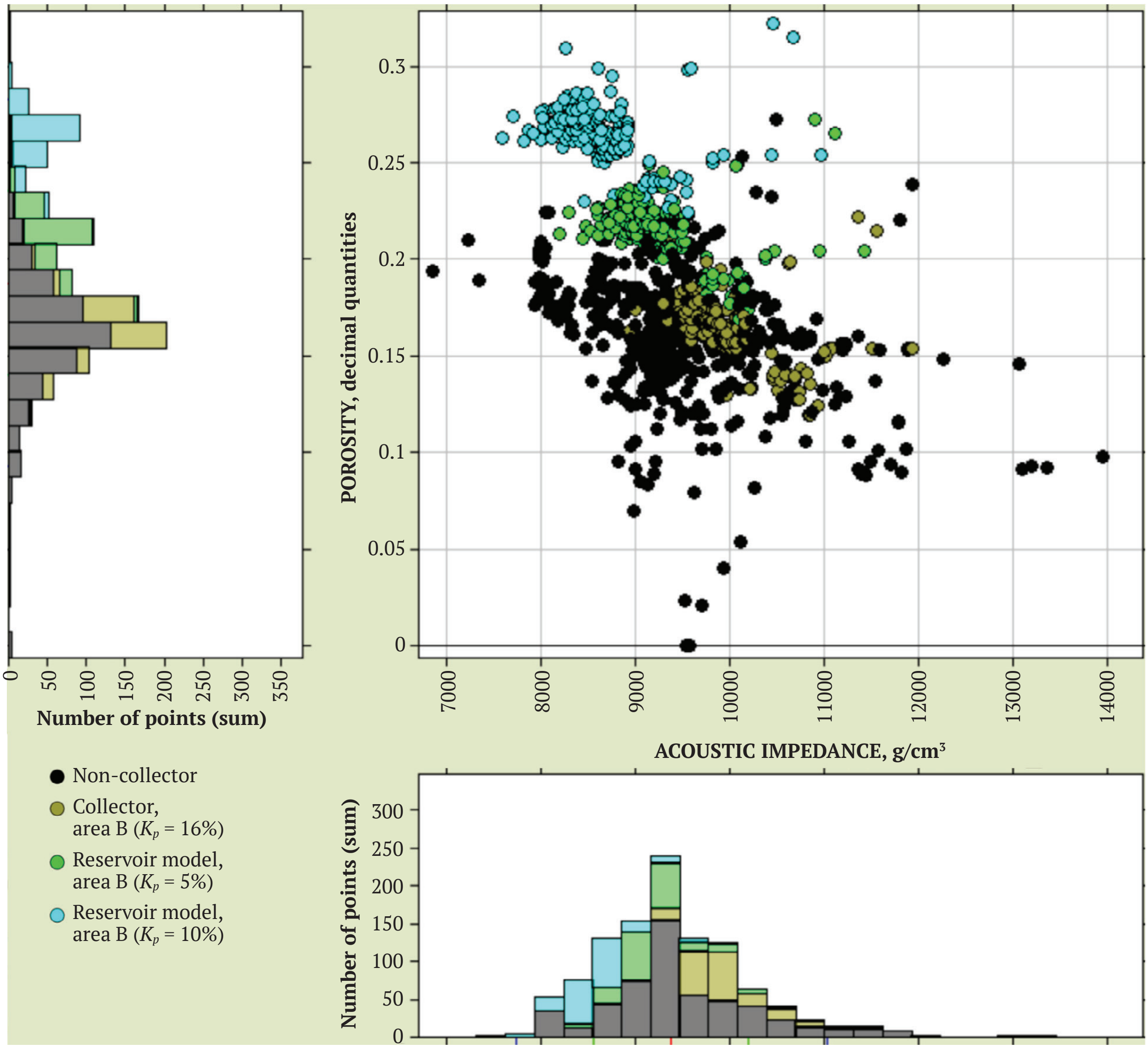

Fig. 4. Results of petroelastic modelling using Upper Permian terrigenous sediments as an example. Cases of possible values of porosity in the reservoir were simulated according to a priori information from analogue deposits

porosity values of about 26%, the difference between a collector and non-collector in the acoustic impedance field is weakly manifested.

Consequently, there may be zones of reservoir spreading in the area with simulated porosity values, but they are not likely to appear in the field of elastic parameters (“missing the target”).

The chaotic distribution of reservoir and non-reservoir points in cross-plots in prospective intervals in the carbonate part of the sequence is explained by the lack of well data for the area and the complexity of the reservoir structure, which does not allow high-quality modelling and assessment of the ability to predict rock properties in the inter-well space.

In this case, based on the results of a comprehensive analysis of well data, it is impossible to quantitatively predict permeability and porosity in the inter-well space from available materials of CDP-3D seismic data dynamic analysis. Only a qualitative interpretation technique using wavefield attributes is applicable here, where the acoustic inversion results are an additional attribute that characterises the acoustic impedance of a horizon.

The application of the attribute analysis techniques allows some anomalies identified with geological features that could potentially be hydrocarbon traps in the investigated areas to be identified and traced. The additional application of analogy and a priori geological information makes it possible to perform a generalised interpretation of selected seismic-facial units that have been confirmed on seismic sections.

The results of the dynamic analysis of the CDP-3D seismic data are shown in Fig. 5. The following has been established:

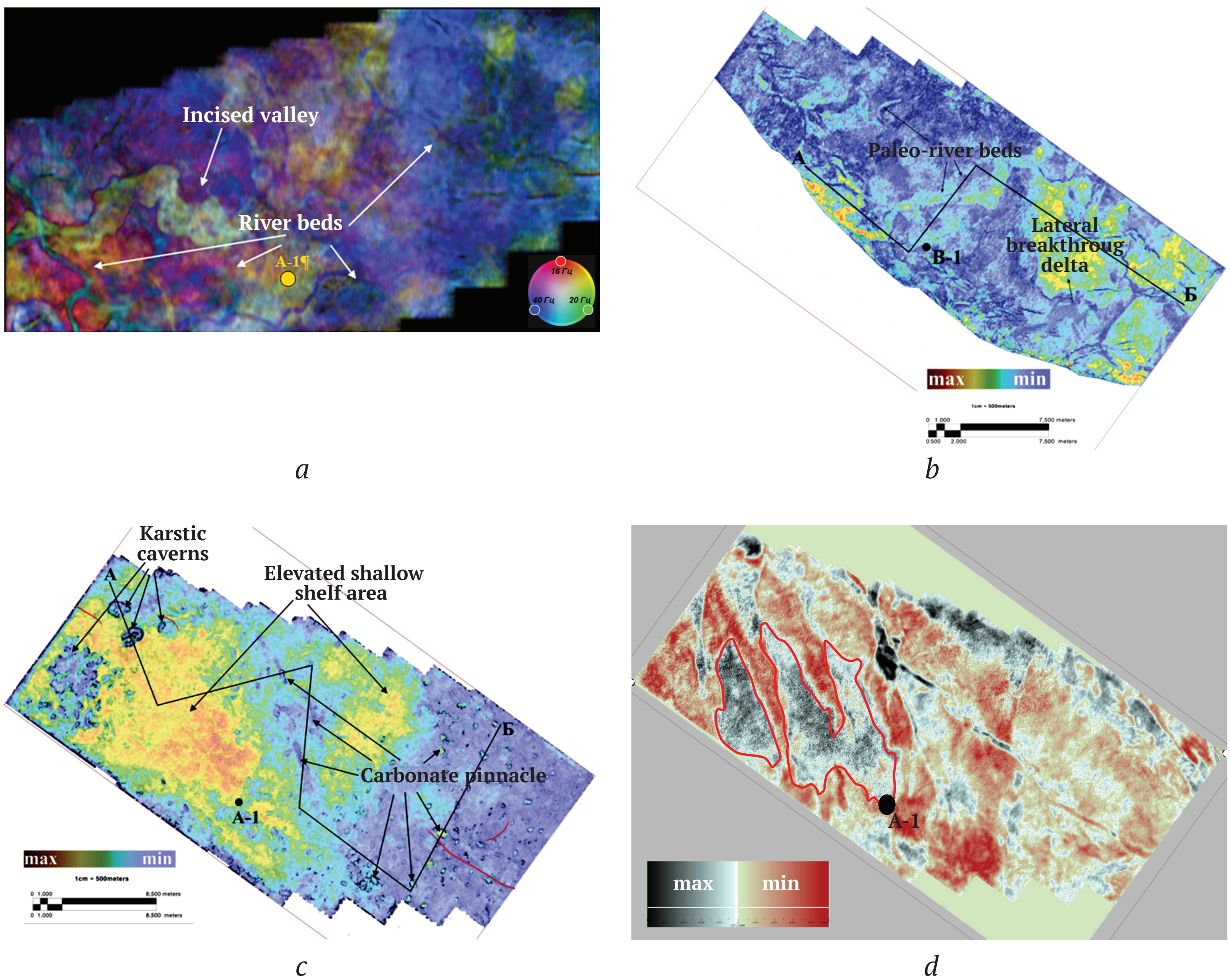

Fig. 5. Attribute map:
a – spectral decomposition in the Upper Permian roof interval (area A); *b* – RMS (RMS amplitudes) – amplitudes in the Upper Permian reservoir bed interval (area B); *c* – complex RMS amplitude and coherence attribute in the Lower Permian sequence interval (area A); *d* – horizontal slice of amplitudes in the Lower Silurian sequence interval (area A)

In the Upper Permian interval of the sequence, a system of branched channel bodies striking northeast. A northwest-trending alluvial valley formed at the turn of the Permian and Triassic periods in area A, has been identified. The in-channel nature of the productive sand bed of Area B was established and the area of its spreading was mapped;

In the **Upper Carboniferous-Lower Permian sequence part, within which carbonate platform with organogenic structures of "pinnacle" type occur, karsting zones have been identified;**

In the Silurian sequence part, paleo-incision-type anomalies formed during the Early Devonian, faults and the productive horizon shear zones have been identified. A pay zone (with non-commercial oil influx) interpreted as an organogenic structure (pinnacle) was found further down in the sequence. The pay zone is located in an elevated block, which is quite typical geologically for carbonate structures under similar conditions.

Conclusions (Findings). The research findings gave a different perspective on the area's potential. Detailed structural and tectonic models of promising deposits were built: a qualitative prediction of zones with improved permeability and porosity was performed; additional hydrocarbon exploration targets were identified; the resource base of the area was doubled, and the risk of drilling empty wells was reduced. Thus, it proves the effectiveness of dynamic analysis at all stages of exploration.

Example 3. A method for predicting hydrocarbon reservoir parameters estimation to improve the geological efficiency of mapping net pay thicknesses and permeability and porosity of reservoirs

As a rule, permeability and porosity maps of reservoir bed properties and maps of total and net pay thicknesses are built to quantitatively predict the estimation parameters of hydrocarbon reservoirs. The maps, built with minimum error, allow specialists to determine the optimum location of wells in the best reservoirs with maximum net pay thicknesses, thereby minimising drilling risks.

The standard mapping algorithm is described in many training manuals and implemented in numerous software tools. The input data are the results of geophysical well logging interpretations, core sampling studies, formation testing and sampling. In an inter-well space, reservoir position, distribution of porosity & permeability and reservoir bed thicknesses are determined in accordance with seismic data [11].

AThe authors propose a new approach to predicting high-yield hydrocarbon reservoirs. Analysis of both Russian and foreign literature sources has shown that this particular method is not yet widely used in the oil and gas geological and scientific community.

Within the framework of the presented methodology, hydrocarbon reservoir parameters were predicted using reservoir parameters: net pay thickness (h_{np}) and the product of net pay by porosity factor (K_p), $K_p \cdot h_{np}$, and total thickness of the potential reservoir bed ΔH.

Initially, reservoir parameters are determined from the interpretation of geophysical well data. The following regression relationships are then plotted: $h_{np} - \Delta H$, $K_p \cdot h_{np} - \Delta H$. The result is an equation that is used to build net pay maps and predictive reservoir maps. Type of the graph, linear or polynomial, is selected depending on the value of the correlation coefficient R^2 which determines the accuracy of the calculations. If the input parameters are satisfactorily matched, it should not be less than 0.5. The R^2 value depends on the quality and quantity of the input data (wells, well logging data). The higher the R^2 value, the higher the quality of the constructs and forecasts.

The main criterion for selecting the recommended well point on the predict maps of reservoir parameters will be the maximum values of porosity coefficients K_p and effective oil and gas saturated thicknesses h_{ef} of reservoir formations. Let's consider an example.

The Ermolovsky subsoil block is located in the central part of the Izhma-Pechorskaya Depression within the Lem'yusky step in an old mining area with developed infrastructure. No oil or gas deposits have been identified in the area from the previously drilled wells. However, the results of reinterpretation of old logging, new data from geophysical studies of well 1-Ermolovskaya and the CDP-2D seismic data served as the grounds for a detailed exploration to be conducted here, namely the CDP-3D seismic survey. Based on the CDP-3D seismic data, two structures have been prepared for drilling, Sedvozhskaya and Vostochno-Sedvozhskaya, and well locations were identified.

A quantitative prediction of the parameters of the predicted oil reservoirs was made to determine the order of drilling priority (Fig. 6). In graphs and maps characterizing the dependence of net pay thickness and products of net pay thickness by porosity $K_p \cdot h_{np}$ values on total reservoir bed thickness ΔH, the point of the recommended well 1 has the highest position and is characterized by maximum values. The graph type is polynomial. The correlation coefficient is 0.852, indicating high accuracy of the prediction made.

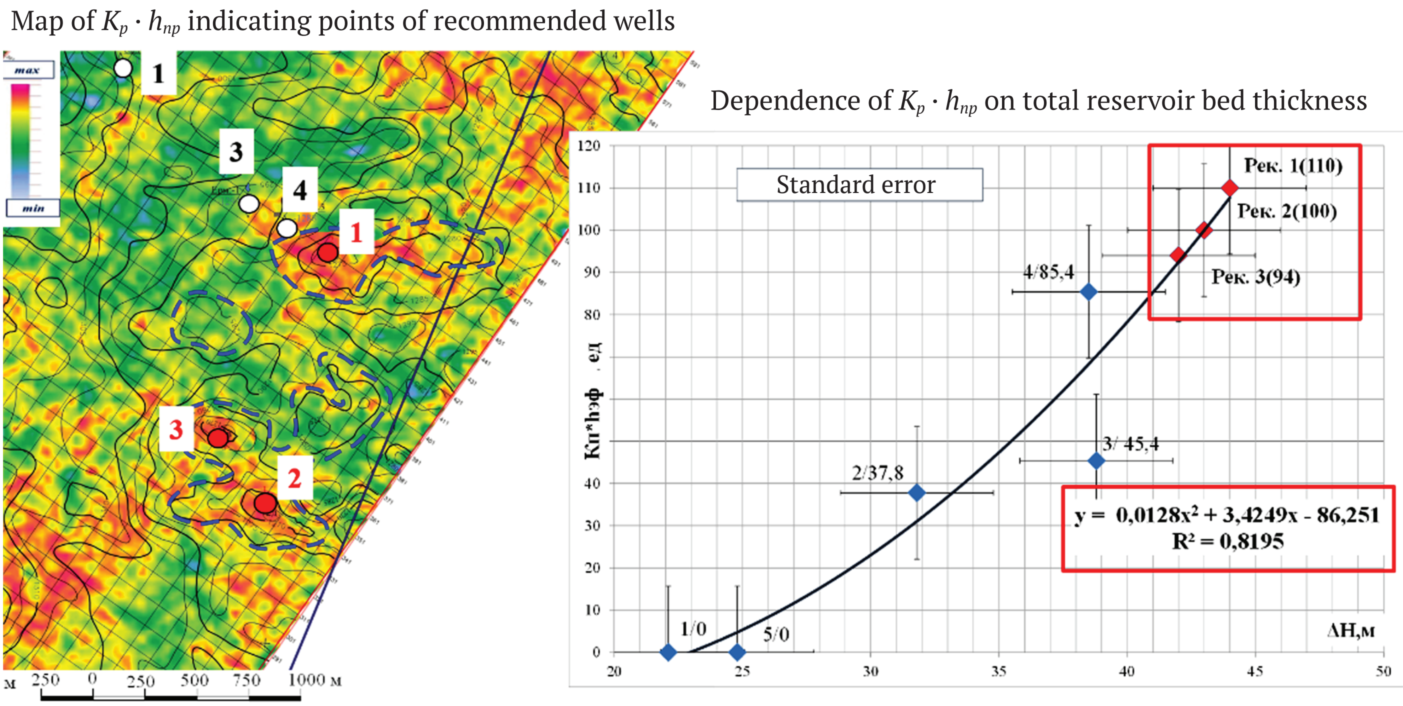

Fig. 6. An example of quantitative reservoir permeability and porosity prediction. F5 layer (D3up). Yermolovskaya area (based on materials from the Institute of Oil and Gas Problems of the Russian Academy of Sciences (IPNG RAS))

Conclusions (Findings). The method proposed by the authors for predicting parameters of hydrocarbon reservoirs will allow to determine the maximum effective oil and gas saturated thicknesses within the mapped traps.

Maximum values of porosity coefficients K_p and effective oil and gas saturated thicknesses hnp of reservoir beds in the shielded volume indicate highly profitable hydrocarbon deposits. In this regard, the application of the proposed regression relationships in the prediction of hydrocarbon discoveries will allow to place the wells directly within the maximum values and thus increase efficiency of drilling.

Unfortunately, no wells have been drilled on the site so far. However, the effectiveness of the proposed methodological approach has been proven at the North Khosedayuskoye and North Mukerkamylskoye oil fields, where wells were drilled with flow rates of more than 100 t/day obtained from the Lower Carboniferous Serpukhoian carbonates and Upper Devonian Nyumylg-Zelenetsky reefogenic sediments.

Conclusion

The proposed scientific approach to the historicalandgenetic method for predicting hydrocarbon traps and reservoirs revealed three possible lithologically constrained traps, thereby increasing the oil and gas potential of the area, and made it possible to adjust the further exploration program.

The results of dynamic analysis, which is widely used in domestic and foreign practice at drilled areas and fields, confirmed the feasibility of its application at structures that have been poorly explored by drilling or withdrawn from drilling programs, as well as for the prospecting of missed deposits.

The values of reservoir bed parameters (h_{np}, $K_p \cdot h_{np}$) obtained through the interpretation of geophysical data and their regression relationships ($h_{np} - \Delta H$, $K_p \cdot h_{np} - \Delta H$) constitute the basis for constructing predictive maps of net pay thicknesses and high-capacity reservoirs as well as their quantitative prediction. These maps then allow wells to be positioned directly into the points of the maximum values, thereby increasing drilling performance and exploration efficiency.

The presented technologies for detecting oil and gas prospective traps and prediction of estimated parameters of hydrocarbon reservoirs will ensure the conditionality of prospect preparation and thereby increase the quality of planning and efficiency of exploration by reducing the number of drilled unproductive wells. This will improve the accuracy of the estimates of predicted and discovered deposits resources and reserves.

Application of the presented methodological approaches to prediction and prospecting of hydrocarbon deposits can become a substantial addition at any stage of exploration work within the Timan-Pechora oil and gas province and in other oil and gas bearing regions of the country.

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BENEFICIATION AND PROCESSING OF NATURAL AND TECHNOGENIC RAW MATERIALS

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Selection of Temperature regimes for conditioning and flotation of diamond-bearing kimberlite with compound collectors

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Abstract

The condition for stable fixation of a collector on the surface of diamonds and their flotation is the use of collectors of the optimal fractional composition and the choice of the optimum temperature regime of the process. To determine the parameters of the diamond flotation regime, the regularities of the phase transitions of asphaltene-tar fractions at increasing temperature and diluting F-5 with technical diesel fraction were established. It was demonstrated that increasing the collector temperature leads to the transfer of asphaltene-tar fractions to a dissolved and finely dispersed state. To an even greater extent, dissolving asphaltene-tar fractions is facilitated by the addition of medium- and low-molecular weight fractions of oil, for instance, a technical diesel fraction.

It was revealed that the KM-10, KM-14, and KM-18 reagents, being compounds of F-5 fuel oil with technical diesel fraction (10–18 % DF), were characterized by optimal viscosity and ability to displace aqueous phase from a diamond surface, thus ensuring stable hydrophobization and high floatability of diamonds. The optimal temperature regime has been selected, which involved maintaining the temperature at the stage of conditioning with the collector at +30–40 °C, at which the maximum selective fixation of compound collectors on the diamond surface, characterized by the value of the limiting wetting angle, was achieved.

The flotation tests have confirmed that the best results are achieved at a temperature of +30–40 °C at the conditioning stage and +14–24 °C at the flotation stage. At +24 °C, the best results were obtained for the relatively less diluted KM-10 and KM-14 fuel oils obtained by diluting F-5 fuel oil with a technical diesel fraction at the diluent volume fractions of 10 and 14 %. The diamond recovery achieved in the flotation tests was 3.8–4.5 % higher than when using the traditional collector, F-5 fuel oil. At +14 °C, the highly diluted fuel oil, KM-18 with a volume fraction of 18 % of the technical diesel fraction, demonstrated better collecting abilities.

The optimal compositions of the collector and the regimes of feed preparation and flotation were tested at a foam separation unit. The tests showed that it is possible to increase diamond recovery into concentrate by 2.3–4.5 %. The recommendations are provided on the use of thermal conditioning in the foam separation cycle and maintaining the conditioning medium temperature at +30–40 °C and the foam separation temperature at +14–24 °C.

Keywords

diamonds, kimberlite, collector, fractional composition, conditioning, wetting, foam separation, heat treatment

For citation

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ОБОГАЩЕНИЕ, ПЕРЕРАБОТКА МИНЕРАЛЬНОГО И ТЕХНОГЕННОГО СЫРЬЯ

Научная статья

Выбор температурных режимов кондиционирования и флотации алмазосодержащих кимберлитов компаундными собирателями

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Аннотация

Условием устойчивого закрепления собирателя на поверхности алмазов и их флотации являются применение собирателей оптимального фракционного состава и выбор необходимого температурного режима технологических операций. С целью определения параметров режима флотации алмазов установлены закономерности фазовых переходов асфальтено-смолистых фракций при повышении температуры и разбавлении мазута Ф-5 дизельной технической фракцией. Показано, что увеличение температуры собирателя приводит к переводу асфальтено-смолистых фракций в растворенное и тонкодисперсное состояние. В еще большей мере решению задачи растворения асфальтено-смолистых фракций способствует добавление средне- и низкомолекулярных фракций нефти, например, дизельной технической фракции.

Показано, что реагенты КМ-10, КМ-14 и КМ-18, представляющие собой компаунды мазута Ф-5 с дизельной технической фракцией (10–18 % ДФ), характеризуются оптимальной вязкостью и способностью вытеснять водную фазу с поверхности алмаза, что обеспечивает возможность устойчивой гидрофобизации и высокую флотируемость алмаза. Выбран оптимальный температурный режим, который предполагает поддержание температуры в операции кондиционирования с собирателем +30–40 °C, при котором достигается максимальная склонность компаундных собирателей к селективному закреплению на поверхности алмазов, характеризуемая величиной краевого угла смачивания.

Флотационными опытами подтверждено, что наилучшие результаты достигаются при температуре среды +30–40 °C в операции кондиционирования и +14–24 °C при флотации. При +24 °C наилучшие результаты получены для относительно менее разбавленных мазутов КМ-10 и КМ-14, полученных разбавлением мазута Ф-5 дизельной технической фракцией с объемной долей разбавителя 10 и 14 %. Достигнутое извлечение алмазов при флотации на 3,8–4,5 % выше, чем при использовании базового собирателя – мазута Ф-5. При +14 °C лучше проявляет собирательные свойства мазут с большим разбавлением – КМ-18 с объемной долей дизельной технической фракции 18 %.

Оптимальные составы собирателя и режим подготовки питания и флотации апробированы на установке пенной сепарации, где показали возможность повышения извлечения алмазов в концентрат на 2,3–4,5 %. Даны рекомендации по применению теплового кондиционирования в цикле пенной сепарации и поддержанию температуры среды в операции кондиционирования +30–40 °C и в операции пенной сепарации +14–24 °C.

Ключевые слова

алмазы, кимберлиты, собиратель, фракционный состав, кондиционирование, смачивание, пенная сепарация, тепловая обработка

Для цитирования

Morozov V.V., Kovalenko E.G., Dvoichenkova G.P., Chut-Dy V.A. Selection of Temperature regimes for conditioning and flotation of diamond-bearing kimberlite with compound collectors. *Mining Science and Technology* (*Russia*). 2022;7(4):287–297. https://doi.org/10.17073/2500-0632-2022-10-23

Introduction

The foam separation process, which constitutes the main method of extracting small diamonds from kimberlite, involves the use of various oil products as collectors, including oil, F5 bunker fuel oil, and water-oil emulsions [1, 2]. Changes in the fractional composition of the oil products to be used as collectors as well as fluctuations in the temperature of the flotation pulp often lead to deterioration of the foam separation performance [3]. Insufficient fixation of the apolar collector on the diamond surface due to hydrophilisation of the diamond surface or inefficiency of the collectors is the main reason for the decrease in recovery [3, 4]. Increasing the stability of the collector fixation on the surface of diamonds and, as a result, increasing their floatability can be ensured by using methods for restoring the natural floatability of diamonds through selecting collectors of optimal fractional composition and maintaining the required temperature regime at conditioning and foam separation stages [5–7]. To improve the performance of diamond-bearing kimberlite foam separation, the physicochemical properties and optimum component composition of the collectors were studied in the course of this study, and the temperature regimes for the key stages of the technological process were selected.

1. Research techniques

The research of the structure of oil products used as a collector was carried out by the combined ultraviolet and visible light microscopy method [8]. Micrographs of a thin layer of the oil products were obtained by a Micromed-3-LUM microscope. Visiometric analysis and determining particle size distribution characteristics of asphaltene-tar fractions were carried out using the VideoTest 4.0 software package [9].

A SV-10 vibrating viscometer [10] was used to measure dynamic viscosity of the reagents. An important advantage of the method and device used is the possibility of obtaining continuous dependences of viscosity on temperature both in sample cooling and heating regimes.

To measure the limiting wetting angle of diamonds and kimberlite by a drop of collector in an aqueous phase, an OCA 15EC device with a USB-camera and a SD-DM direct dosage system for liquid was used in combination with ES electronic dosing module [11]. In the research, an improved measurement technique described in the relevant section of the paper was used.

Verification of collecting abilities of the studied petroleum products and their mixtures was carried out using Hallimond tube, a non-frothing flotation unit with a porous glass aerator (Schott filter) [12]. The preparation of diamonds for testing involved chemical cleaning of their surfaces, which included washing in carbon tetrachloride, alcohol, distilled water, and treatment in concentrated hydrochloric acid solution. Individual mineral samples and mixtures of diamond and kimberlite grainsof smaller size were used. The semi-industrial tests with the best collectors at selected temperature regimes were carried out at the LFM-001S foam separation unit of Yakutniproalmaz Institute with the use of industrial recycled water. Specific test conditions are outlined in the relevant sections of this paper.

2. Study of temperature and fractional composition effect on the structure and viscosity of petroleum products

The temperature of the medium at the stage of initial feed conditioning with flotation reagents and immediately in the flotation process is an important parameter of the foam separation process [7, 13]. Another important factor determining diamond flotation performance is the structure of a collector used, in particular, the form of adhesion-active high molecular weight fractions [14, 15]. The structure of petroleum products is largely determined by the ratio of low and high molecular weight fractions and the temperature of the medium. To substantiate the optimal temperature regime of the diamond-containing products conditioning and flotation processes, studies were carried out with a view to determining the effect of temperature on the structure of the used petroleum product on the example of the basic collector being used, F-5 bunker fuel oil. The research examined the temperature range from −10 °C to +50 °C, due to the specific storage and use regimes of the collectors.

For physical, chemical, and technological research, samples of F-5 bunker fuel oil and technical diesel fraction were taken. Bologoenefteprodukt LLC, according to the method developed by the IPCON RAS, prepared compound collectors consisting of F-5 fuel oil and technical diesel fraction from industrial products. The mass fraction of asphaltene-tar fractions in the initial F-5 fuel oil was determined using the standard procedure as per GOST 2177-99 (ISO 3405-88).

Analysis of the results of the collector structure studies showed that when F-5 fuel oil is cooled to a temperature of −10 °C, grains of the asphaltene-tar fraction and paraffin were crystallized, and droplets of low molecular weight petroleum fractions were condensed (Fig. 1, *a*). When bunker fuel oil was heated to a temperature of +10 °C, droplets of low molecular weight fractions disappeared due to the mutual dissolution of the phases, while the asphaltene and paraffin crystals survived, however, in smaller quantities (Fig. 1, *b*). When heated to +24 °C (Fig. 1, *c*), optically distinct paraffin crystals practically disappeared. When further heated to +50 °C, paraffin crystals were not detected, and the amount of tars and asphaltenes decreased (Fig. 1, *d*).

The results of optical-visiometric analysis of the particle size distribution of the asphaltene-tar fraction grains, represented as a mass fraction of the substance in solid and dissolved phase state as a function of temperature, revealed a pattern of their dispersion and dissolution with increasing temperature. As can be seen from Fig. 2, the mass fraction of asphaltene-tar fraction grains of optically discernible size (+0.1 microns) decreases from 28.1 % at a temperature of −10 °C to 20.2 % at a temperature of +50 °C.

Analysis of the particle size distribution characteristics of the asphaltene-tar fraction grains in the range of 0.1 to10 µm shows that heating the reagent leads to a proportional dissolution of both large and small grains, resulting in insignificant changing the particle size distribution.

Thus, the results obtained show that an increase in temperature contributes to the dissolution of the fraction of tars and asphaltenes. To maximize the dissolution of asphaltenes in low molecular weight fractions, heating up to +40–50 °C is required.

Changing the structure of petroleum products by the addition of low molecular weight hydrocarbon fractions, for instance, a technical diesel fraction, is a well-known way to regulate their physicochemical properties [2, 16]. When using fuel oil as collectors, the use of additives of the technical diesel fraction or its analogues (diesel fuel, bunker fuel, domestic light fuel) provides not only the required properties, for instance, a decrease in the pour point, but also increases its collector capacity in relation to diamonds [17].

Dilution of fuel oils with low molecular weight petroleum refining fractions causes a significant decrease in viscosity, pour point, and flash point. The physicochemical properties of petroleum products vary with their phase composition changes due to changing the disperse structure of petroleum, including the phase state of high molecular weight components, primarily asphaltene-tar fraction [18].

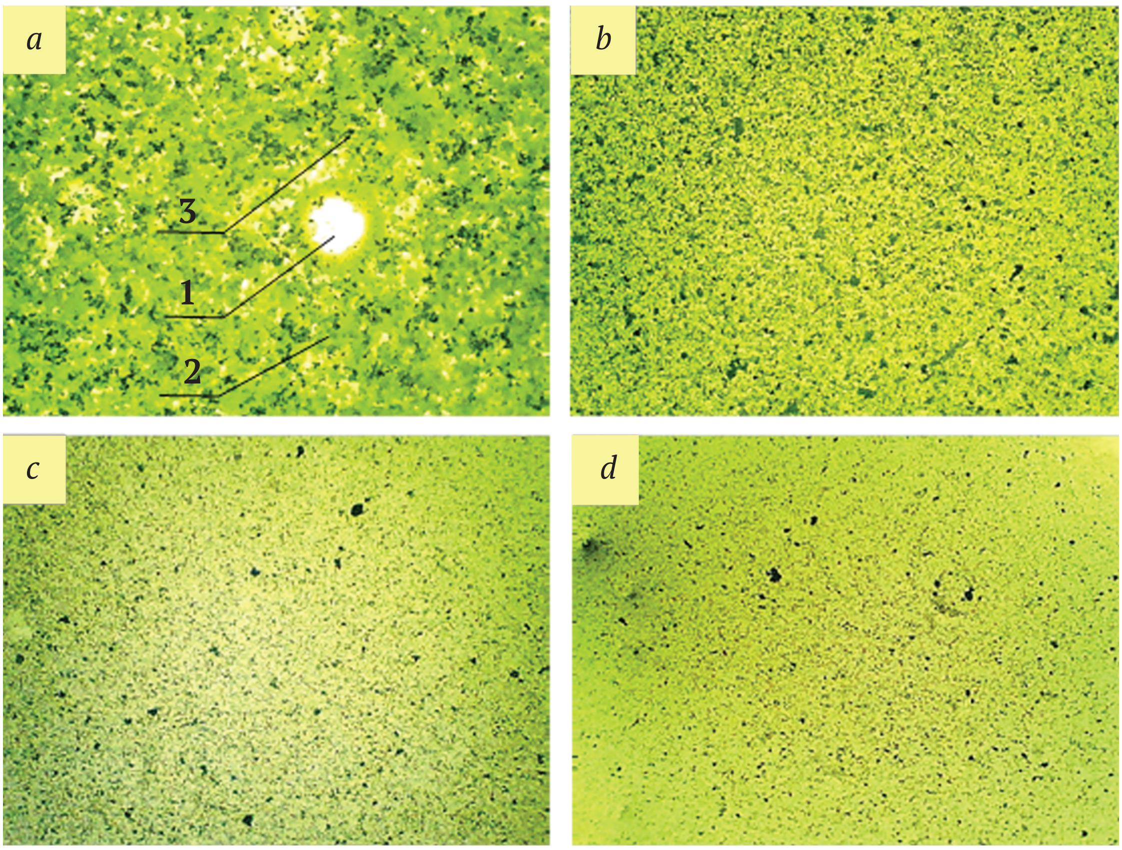

Fig. 1. Micrographs of a thin layer of M-5 fuel oil at the combined lighting conditions at Micromed-3-LUM microscope after cooling to a temperature of −10 °C (*a*), heated to a temperature of +10 °C (*b*), +24 °C (*c*), and +50 °C (*d*): *1* – drops of low molecular weight hydrocarbon fractions, *2* – crystals of saturated hydrocarbons (paraffins); *3* – grains of asphaltene-tar fractions

The results of visiometric analysis of the phase composition of the asphaltene-tar fraction, represented in the form of dependences of the proportion of types of asphaltene-tar fractions on the degree of the dilution of F-5 fuel oil with diesel fraction, demonstrated a significant effect of low molecular weight hydrocarbon additives on the structure of the petroleum product. According to the results of optical-visiometric analysis, the proportion of asphaltene-tar fractions with a grain size of more than 0.1 μm (detectable by the applied technique) decreases from 25 % to 4.5 % when diluted to 30 % with diesel fraction. Taking into account the natural decrease in the mass fraction of tars and asphaltenes when diluted, their proportion in finely dispersed, colloidal, and dissolved forms increases from 3.7 to 15.7 absolute percents or from 13.0 to 55.1 relative percents (Fig. 3).

Analysis of the results obtained shows that the dilution of fuel oils with low molecular weight fractions is the most effective factor in dissolving the tar and asphaltene fraction.

Viscosity is another characteristic of petroleum products that significantly affects the effective interaction of the collector with the diamond. As shown in study [2], the best results of foam separation of diamond-containing kimberlites are achieved using the compounds of fuel oil with diesel fuel or petroleum-water emulsions in the viscosity range of 12–19 MPa·s (for a standard temperature of +50 °C).

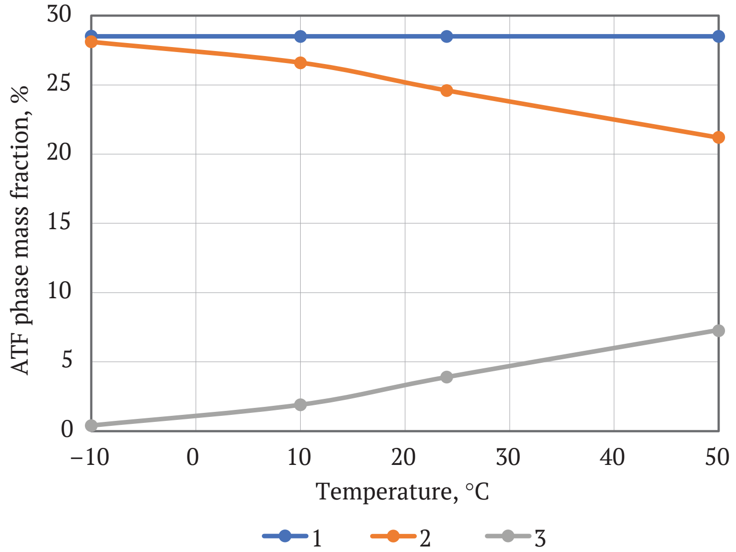

Fig. 2. Asphaltene-tar fractions (ATF) portion as a function of medium temperature:
1 – total; *2* – in solid form based on the results of visiometric analysis;
3 – in dissolved and emulsion form (as a difference between the first two values)

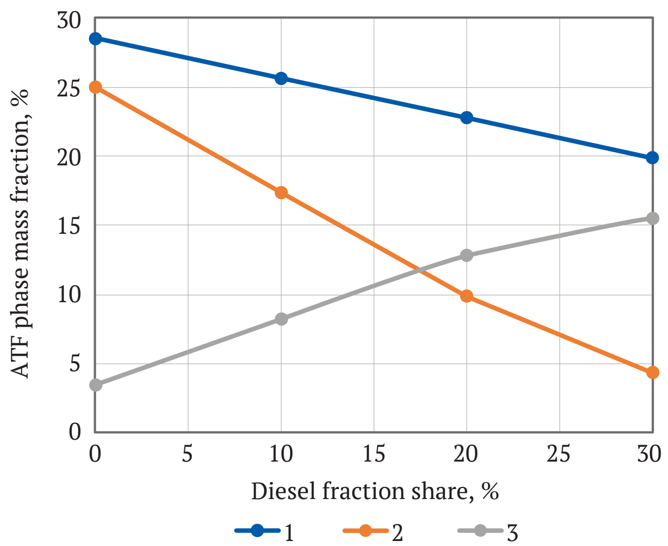

Fig. 3. Change in the asphaltene-tar fractions (ATF) phase proportions when F-5 fuel oil is diluted with a diesel fraction:
1 – total; *2* – in solid form based on the results of visiometric analysis; *3* – in dissolved and emulsion form

The viscosity of fuel oils depends significantly on the temperature and their fractional composition. As shown in Table 1, a decrease in the fuel oil temperature from +50 to +14 °C leads to an increase in the viscosity several times. The studies using an SV-10 device showed that at a standard temperature of +50 °C the viscosity of petroleum products used as collectors varies in the range of 12.3 to 119 MPa·s. At the common foam separation process temperature of +14 °C, the viscosity increases several times and range 32.2 to 1,100 MPa·s. When the temperature decreases to +10 °C, straight-run fuel oil and M-40 fuel oil solidify. The viscosity of F-5 fuel oil reaches more than 1000 MPa·s.

Table 1

The viscosity of petroleum products at different temperatures

Product	Temperature, °C			
	+50	+25	+14	+10
Straight-run fuel oil	119.0	155.0	1100	Solidified
M-40 fuel oil	72.0	119.0	158.5	Solidified
F-5 fuel oil	32.5	64.5	119.6	1090
F-5 fuel oil + 10 % of Diesel fraction	12.3	17.5	32.2	45.2
Diesel fraction	0.98	1.64	3.6	5.8

Analysis of the data presented in Table 1 shows that industrial fuel oils exhibit higher viscosities (32.5–119 mPa·s) than those recommended in the research [14]. The compound of F-5 fuel oil with diesel fraction of 10 % (the viscosity of 12.3 MPa·s, Table 1) exhibits rather acceptable characteristics. Varying the degree of dilution of fuel oil with low molecular weight petroleum products makes it possible to achieve various viscosity values within the recommended range from 12.3 to 119 mPa·s.

Thus, the research findings demonstrated that temperature changes and dilution with low molecular weight fractions constitute effective factors in regulating the structure of asphaltene-tar fractions of fuel oil and its physicochemical properties.

3. Studies of the temperature effect on the interaction of diamonds and minerals with a collector

The most informative technique that assesses the ability of reagents to fix on the surface of minerals is the method of measuring three-phase limiting wetting angles. For the mineral – collector droplet – aqueous phase system (Fig. 4), the measured limiting (three-phase) wetting angle is determined by the relationship between oleophilicity (increase in the wetting angle) and hydrophilicity (decrease in the wetting angle) of the mineral surface [18].

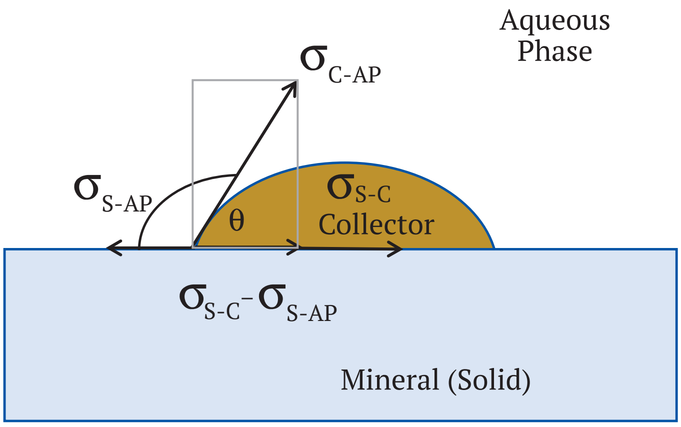

Fig. 4. Schematic representation of a collector droplet on a mineral in a cuvette filled with an aqueous phase

To adequately simulate the actual conditions of the industrial process, an improved testing method was used, which included preliminary wetting of the mineral sample with a thin layer of water, applying a collector droplet to the wetted surface, and increasing the liquid level above the sample surface. Such conditions allow simulating both the process of fixing the collector on a mineral in the course of conditioning (Fig. 5, *a*) and its separation under the influence of external factors (the influence of the difference between the collector density and the aqueous phase density or hydrodynamic separation). The distribution of the collector between the sample surface and the surface of the aqueous phase (parts of the collector that have emersed due to the difference in the specific weights of water and the collector, Fig. 5, *b*) leads to preserving collector droplets on a hydrophobic sample with the formation of an equilibrium limiting wetting angle or completely separating the collector droplets from the hydrophilic mineral.

When processing a kimberlite, which is a polymineral rock, a collector is fragmentary fixed on naturally hydrophobic mineral-constituents of the kimberlite.

Before conducting measurements, the initial sample (diamond or kimberlite) was soaked in recycled water in contact with air for one hour and then the cuvette with the mineral sample was cooled or heated under thermostatic conditions in the range of +10–70 °C. This ensured maintaining the sample and performing the tests to measure the limiting wetting angles in the temperature range of +14–60 °C.

The composition of the recycled water corresponded to the recycled water of PP No. 3 of Mirny GOK. F-5 fuel oil was used as a collector. The research results showed a mild dependence of the limiting wetting angle on the temperature of the aqueous medium. The limiting wetting angle, which characterizes the hydrophobicity of a diamond and its tendency to interact with the collector, gradually increases in the temperature range of +14–40 °C. The difference in limiting wetting angles at a temperature of +14 and +40 °C was 3–5 degrees (Table 2). A further increase in the temperature does not lead to an increase in the limiting wetting angle.

The hydrophobicity of hydrophobic kimberlite minerals (phlogopite, talc, etc.), similar to that of diamond, increases slightly with increasing temperature. The increase in temperature has a positive effect on hydrophilic kimberlite minerals (olivine, calcite), reducing their hydrophobicity until the cessation of the droplet fixing on the mineral surface at a temperature of +30 °C and above (Table 3). In most cases, a droplet separates from the surface of the kimberlite section, and fuel oil is fixed only to certain areas of the surface, which are represented by inclusions of natural hydrophobic minerals, mainly layered aluminosilicates. The droplet is completely detached from the mineral surface at lower (+14–30 °C) and maximum (+60 °C) temperatures.

Analysis of the findings suggests that the optimum temperature regime for the conditioning stage with the collector involves maintaining the temperature at +30–40 °C, when the maximum collector's tendency towards fixing to the diamond surface (identified with the maximum limiting wetting angle) is achieved and there is no significant increase in the collector's tendency towards fixing to kimberlitic minerals.

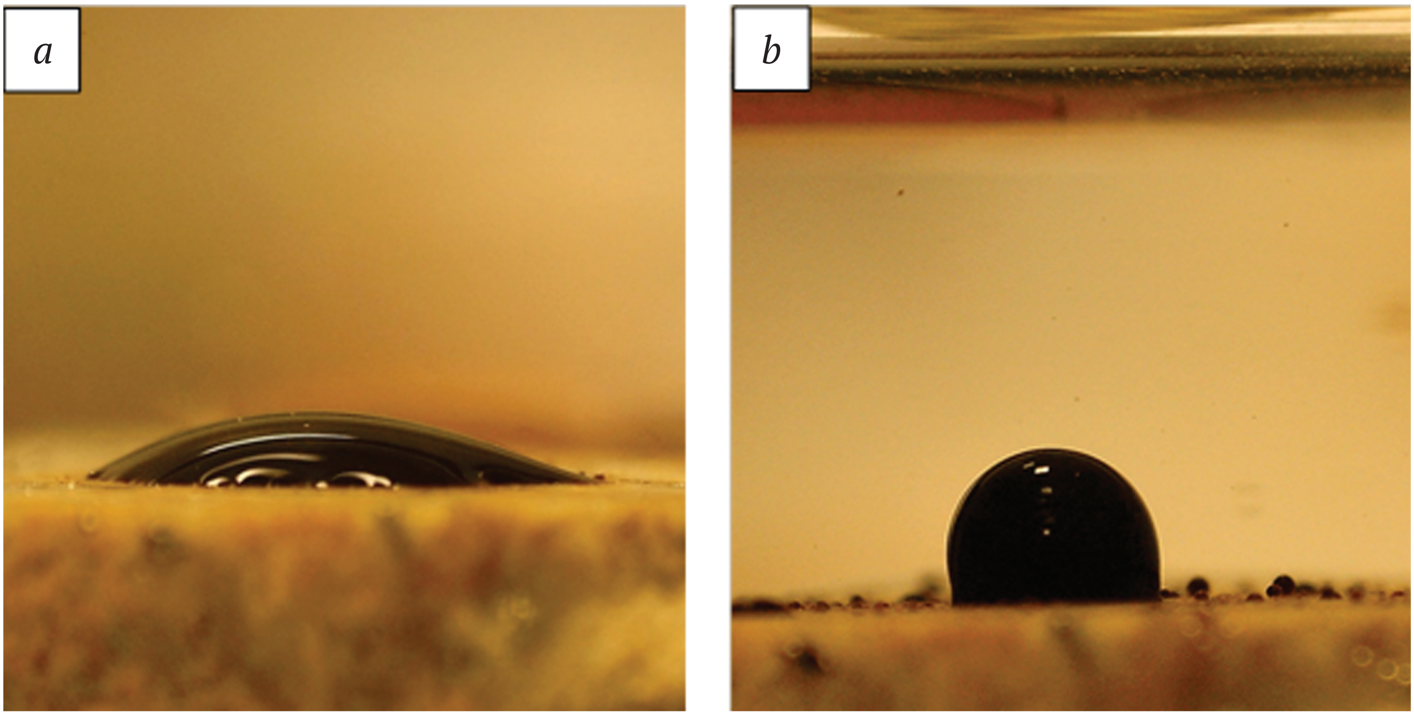

Fig. 5. Images of F-5 fuel oil drop on phlogopite surface:
a – on a moistened thin section; *b* – after the water level rises

Table 2

Changing the limiting wetting angles of a diamond and kimberlite minerals by a droplet of F-5 fuel oil as the temperature increases

Ambient temperature, °C	Limiting wetting angle on minerals, degrees				
	Diamond	Phlogopite	Kimberlite	Calcite	Olivine
+14	91–95	52–67	Separation	42–53	45–55
+24	92–97	54–68	Separation	40–50	40–55
+30	94–101	55–65	Separation	Separation	Separation
+40	94–100	57–66	Fragmentary, 45–75	Separation	Separation
+50	91–96	58–68	Fragmentary, 40–75	Separation	Separation
+60	90–93	60–70	Separation	Separation	Separation

4. Study of the temperature effect in the process stages on the flotation of kimberlite diamonds

The change in the floatability of diamonds when the temperature of conditioning with collector varies was studied based on the results of flotation tests in the Hallimond tube at the conditioning and flotation temperatures of +10, +14, and +24 °C. The selected temperature interval corresponds to the foam separation conditions at industrial plants at different seasons. In the course of the tests, F-5 bunker fuel oil (produced by "Bologoenefteprodukt" LLC) and its compositions with industrial diesel fraction were used.

Taking into account the results of the studies carried out, a temperature of +30 °C was selected for the initial feed conditioning with the collector. The required flotation process temperature (+10–24 °C) was achieved by adding an aqueous phase with a temperature of +6–24 °C. Analysis of the tests results showed that the maximum recovery of diamonds into the concentrate was achieved at temperatures of +14 and +24 °C. At +14 °C, the best results were obtained for KM-10 and KM-14 (diluted fuel oils) obtained by diluting F-5 fuel oil with a diesel fraction at the diesel fraction volumetric proportion of 10 % and 14 % (the recovery of 78.4 and 77.9 %, respectively). This is 3.8–4.5 % higher than that of the best basic collector, F-5 fuel oil (Table 3).

Table 3

Recovery of diamonds in flotation with F-5 bunker fuel oil and its compositions with diesel fraction (DF) as collectors at different temperatures

No.	Collector	Diamond recovery into concentrate, %, in flotation at temperature, °C		
		+10	+14	+24
1	F-5 bunker oil	70.6	74.6	80.5
2	KM-10 diluted fuel oil (10 % DF)	75.4	78.4	84.2
3	KM-14 diluted fuel oil (14 % DF)	74.3	77.9	83.2
4	KM-18 diluted fuel oil (18 % DF)	72.0	75.3	81.5

Further studies were carried out at a non-frothing flotation unit using mineral mixes. A sample of kimberlite (200 mg) was used, into which diamonds (50 mg) were loaded. The size classes used for kimberlite (0.5–0.75 mm) and diamonds (from 0.25 to 0.5 mm) made it possible to analyze the flotation products by sieving and calculate the balance of diamonds and kimberlite.

The test technique included conditioning a sample of kimberlite and diamonds at fixed temperatures (in the range of +24–40 °C). After conditioning, an aqueous phase with a temperature of +12–28 °C was added. After mixing, the medium temperature was set at +14–28 °C, at which the flotation process was carried out. The results of flotation tests with diamond and kimberlite mixes when using heating at the conditioning stage indicated the following. When using F-5 fuel oil, the maximum increase in diamond recovery into the concentrate was achieved by heating the flotation feed at the conditioning stage with the collector up to +40 °C and performing flotation at +28 °C (test 3, Table 4). There was no noticeable change in the recovery of kimberlite into the concentrate when the flotation collector and the temperature regime varied.

For the KM-10 and KM-14 compound fuel oils, the dependence of diamond recovery on temperature is similar and characterized by maximum diamond recovery at the temperatures of +30/24 and +40/28 °C (the temperatures in the conditioning/flotation stages). It is characteristic that when using these compound collectors, diamond recovery is 2.5–3.35 higher than when using F-5 fuel oil. These results coincide with the research data indicating that in this temperature range the optimum reagent viscosity and the maximum limiting angle of wetting of the diamond surface by the collector droplet are achieved. At lower temperatures (+24/14 °C regime), the best performance (among the collectors considered) was demonstrated by the most diluted KM-18 collector (Table 5, tests 4, 7, 10).

The water recycling systems used at the processing plants of Alrosa AK are not designed for thermal conditioning of the recycled water. Therefore, the selected collectors were tested in the conditions of feed preparation close to the standard regime: at the feed conditioning temperature of +24 °C and the foam separation temperature of +16–18 °C.

Table 4

The key process indicators of foam separation using the optimal heating regimes at the conditioning stage

No.	Collector used	Air conditioning/ flotation temperature, °C	Diamond recovery into concentrate, %	Kimberlite yield to concentrate, %
1	F-5 fuel oil	24/14	74.5	1.5
2	F-5 fuel oil	30/24	77.8	1.5
3	F-5 fuel oil	40/28	80.3	1.7
4	KM-10	24/14	77.0	1.9
5	KM-10	30/24	81.2	1.6
6	KM-10	40/28	83.2	1.5
7	KM-14	24/14	77.8	1.7
8	KM-14	30/24	82.2	1.5
9	KM-14	40/28	83.6	1.8
10	KM-18	24/14	80.5	1.3
11	KM-18	30/24	81.2	1.4
12	KM-18	40/28	81.2	1.5

The tests were carried out at a LFM-001S automated foam separation unit of Yakutniproalmaz Institute, equipped with a recycled water system and an automatic air dosing apparatus (Fig. 6).

The LFM-001S foam separation unit (see Fig. 6) operated in practically industrial conditions (collector consumption of 1000 g/t, butyl aerofloat consumption of 50 g/t, a foamer consumption of 150 g/t). The unit used recycled mineralized water from the TSF of No. 3 of Mirny GOK at a rate of the water supply into the under-foam layer of 50 ml/min and an air flow rate of 100 ml/min. Prior to the test, the foamer was added directly to the recycled water of the foam separation unit.

During the tests, the temperature of the mix of kimberlite and diamonds and recycled water was regulated. At the unit, the treatment with the collectors was performed at +24–30 °C, while the foam separation was carried out at +16–24 °C.

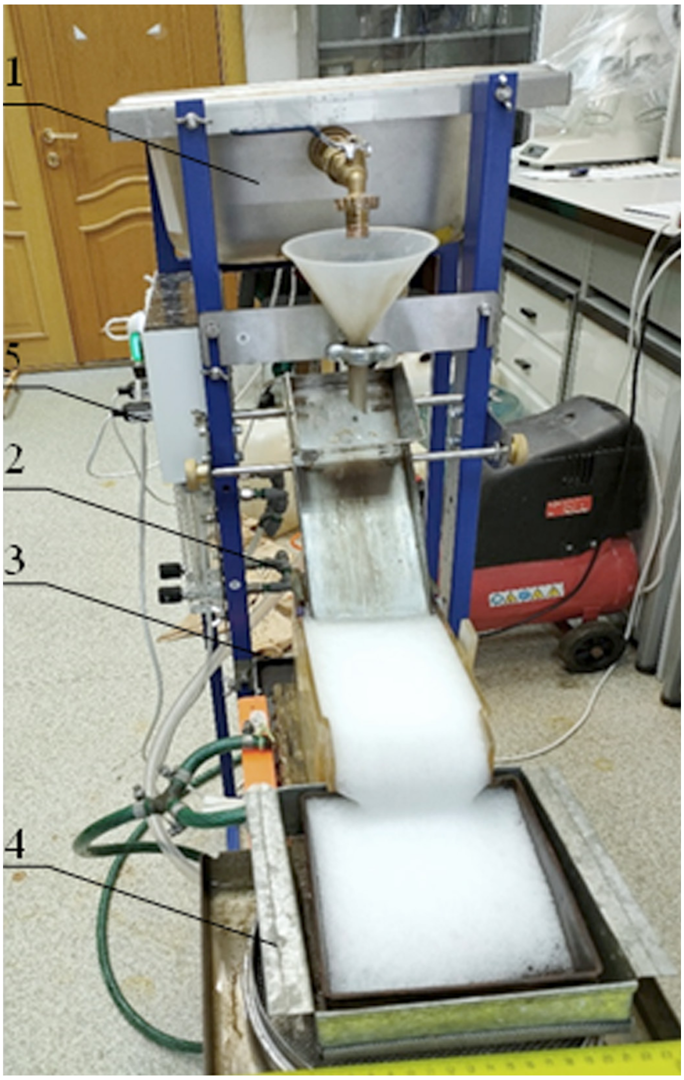

Fig. 6. Automated foam separation unit:
1 – recycled water tank; *2* – supply tray; *3* – working chamber; *4* – concentrate receiver; *5* – unit air flow control

After the foam separation, the products were picked and the extracted diamonds were weighed. As the performance criterion, the selectivity index calculated as a function of diamond recovery (ε) and kimberlite yield into the concentrate (γ) was used:

$$S = \varepsilon - 1{,}3\gamma. \quad (1)$$

The value of 1.3 in equation (1) reflects the ratio between the cost of additionally recoverable diamonds and refinement costs at increased kimberlite yield.

The results of tests on the bench unit (Table 5) indicated the possibility of increasing the recovery of diamonds into concentrate by a maximum of 2.3–4.5 % when using the KM-10 and KM-14 collectors at a temperature regime of +30/18 °C.

Table 5

The performance of the foam separation process at the bench unit

No.	Reagent	Diamond recovery into concentrate, %	Kimberlite yield in concentrate, %	Selectivity, %
1	F-5 fuel oil	79.4	1.7	77.19
2	KM-10	81.7	1.9	79.23
3	KM-14	83.9	2.9	80.13
4	KM-18	80.0	2.4	76.80

When the temperature during the foam separation stage exceeds +24 °C, the diamond recovery increases by 1.0–1.3 %. However, at the same time, the yield of kimberlite into the concentrate also increases, by 1.5–1.8 %, and the selectivity decreases. Therefore, increasing the intensity of thermal conditioning requires adjusting the foam separation reagent regime to prevent an increase in the yield of kimberlite in the diamond concentrate.

Based on the findings of the studies on the effect of temperature on foam separation performance, the recommendations for the use of thermal conditioning in the foam separation cycle and maintaining the conditioning temperature at +30–40 °C and the foam separation temperature at +14–24 °C are provided.

Conclusions

The regularities of dispergation and dissolution of asphaltene-tar fractions when the process temperature increases and F-5 fuel oil is diluted with a diesel fraction, leading to changes in the collector phase composition.

It was shown that the compounds of F-5 fuel oil with a diesel fraction (10–18 % DF) exhibit the required physicochemical characteristics (viscosity and diamond surface wettability), which provide stable fixation of the collector to the diamond surface.

Measurements of the limiting wetting angle revealed that when maintaining the conditioning stage temperature at +30–40 °C, the collector's maximum adhesion to the diamond surface is achieved, while the studied collectors are not markedly fixed to kimberlite minerals.

Flotation tests have shown that the best results are achieved at temperatures of +14 °C and +24 °C. At +14 °C, the highest dilution fuel oil, KM-18 with a volume fraction of 18 % of the diesel fraction, demonstrated better collecting abilities. At +24 °C, the best results were obtained for the relatively less diluted KM-10 and KM-14 fuel oils obtained by diluting F-5 fuel oil with a diesel fraction with the diluent volume fractions of 10 and 14 %, respectively. The diamond recovery achieved (78.4 and 77.9 %, respectively) was 3.8–4.5 % higher than when using fuel oil F-5, the traditional basic collector.

The optimal compositions of the collector and the regimes of feed preparation and flotation were tested at a foam separation unit. They showed the capability of increasing the recovery of diamonds into concentrate by 2.3–4.5 %. These parameters were recommended for the use on an industrial scale.

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BENEFICIATION AND PROCESSING OF NATURAL AND TECHNOGENIC RAW MATERIALS

Research paper

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Effect of sonochemical pretreatment of slurry depressors on sylvin flotation performance

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Abstract
The main source of potassium fertilizers is sylvinite ores consisting primarily of halite (NaCl), silicate and clay-carbonate slurries (clay-salt slurries). Processing of natural potash ores is mainly carried out by the flotation method, which separates KCl, NaCl, and clay-salt slurry. The research is aimed at revealing the effect of sonochemical pretreatment of the depressor reagents, CMC and starch, on dynamic viscosity, aggregate size, electrokinetic potential of these reagent solutions and sylvin flotation performance. It has been established that sonochemical treatment of depressor solutions decreases the size of aggregates of starch molecules by more than 133 times and that of aggregates of CMC molecules from 6 to 4 nm. It has been revealed that sonochemical treatment of anionic CMC solution shifts the electrokinetic potential towards the area of negative values with an increase in acoustic power, while sonochemical treatment of any acoustic power has no effect on the zeta potential of nonionic starch. It has been found that the sonochemical treatment lowers the dynamic viscosity of CMC and starch solutions: the viscosity of CMC solution at a maximum acoustic power of 420 W decreases by 44 % and the viscosity of starch solution at the same acoustic (ultrasonic) power decreases by 70 %. Furthermore, sonochemical pretreatment of sylvin flotation depressors contributes to an increase in KCl recovery and a decrease in the slurry content in the flotation concentrate. The possibility of reducing the consumption of ultrasonic treated depressor is also demonstrated. It is expedient to test the obtained findings in pilot-plant conditions.

Keywords
processing, sylvin flotation, ultrasound, depressor, clay-salt slurry, carboxymethylcellulose, starch, zeta potential, dynamic viscosity, recovery

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ОБОГАЩЕНИЕ, ПЕРЕРАБОТКА МИНЕРАЛЬНОГО И ТЕХНОГЕННОГО СЫРЬЯ

Научная статья

Влияние предварительной сонохимической обработки депрессоров шламов на эффективность сильвиновой флотации

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Аннотация
Основной источник калийных удобрений – сильвинитовые руды, состоящие в том числе из галита (NaCl), силикатных и глинисто-карбонатных шламов (глинисто-солевых шламов). Обогащение природных калийных руд главным образом осуществляется флотационным методом, при котором происходит разделение KCl, NaCl и глинисто-солевых шламов.
Исследование направлено на выявление влияния предварительной сонохимической обработки реагентов-депрессоров – КМЦ и крахмала – на динамическую вязкость, размер агрегатов, электрокинети-

ческий потенциал растворов этих реагентов и на эффективность сильвиновой флотации. Установлено, что сонохимическая обработка растворов депрессоров уменьшает размер агрегатов молекул крахмала более чем в 133 раза, агрегатов молекул КМЦ – с 6 до 4 нм. Выявлено, что сонохимическое воздействие на раствор анионного КМЦ с увеличением акустической мощности смещает электрокинетический потенциал в область отрицательных значений, при этом сонохимическая обработка любой акустической мощности не влияет на дзета-потенциал неионогенного крахмала. Установлено, что сонохимическая обработка понижает динамическую вязкость растворов КМЦ и крахмала: вязкость раствора КМЦ при максимальной акустической мощности 420 Вт снижается на 44 %, вязкость раствора крахмала при той же акустической мощности ультразвука – на 70 %. Кроме того, предварительная сонохимическая обработка депрессоров сильвиновой флотации способствует увеличению извлечения KCl и снижению содержания шламов во флотационном концентрате. Также показана возможность снижения расхода обработанного ультразвуком депрессора. Полученные результаты целесообразно апробировать в опытно-промышленных условиях.

Ключевые слова

обогащение, сильвиновая флотация, ультразвук, депрессор, глинисто-солевой шлам, карбоксиметилцеллюлоза, крахмал, дзета-потенциал, динамическая вязкость, извлечение

Для цитирования

Burov V.E., Poilov V.Z., Huang Z., Chernyshev A.V., Kuzminykh K.G. Effect of sonochemical pretreatment of slurry depressors on sylvin flotation performance. *Mining Science and Technology* (*Russia*). 2022;7(4):298–309. https://doi.org/10.17073/2500-0632-2022-08-09

Introduction

Potassium, along with phosphorus and nitrogen, is the most important component of mineral fertilizers, which enhances the yield of agricultural plants [1–4]. The main source of potash fertilizer is sylvinite ore, which consist of halite (NaCl), silicate and clay-carbonate slurries (clay-salt slurries; hereinafter – CSS) [4, 5]. Beneficiation of natural potash ores is mainly carried out by the flotation method, which separates KCl, NaCl, and CSS [6–8].

Russia hosts one of the world's largest sylvinite ore deposits, the Verkhnekamskoe potassium-magnesium salt deposit, which is rich in valuable sylvinite [9, 10]. To date, however, some of the best sylvinite ore lodes (layers) have already been mined-out at the deposit, and therefore the layers with lower content of sylvinite and with a higher content of CSS are increasingly being used. This leads to the deterioration of the ore processing performance [11, 12]. At the same time, the clay-salt minerals ($CaSO_4$, $MgCO_3$, $CaSO_4 \cdot 0{,}5H_2O$, Fe_2O_3, $CaMg(CO_3)_2$, F^-, $MgCl_2$), which have a greater cation exchange capacity to the salts of primary aliphatic amines used as sylvin flotation collecting agents, produce the greatest adverse impact on the KCl flotation [6, 11, 13, 14]. Competing adsorption of amines on CSS prevents their adsorption on the crystals of potassium chloride that leads to the deterioration or termination of the flotation process [12, 15].

To reduce the CSS content in the ore, mechanical or flotation deslurrying of potassium ores is used prior to the sylvin flotation [12]. However, such methods are incapable of removing CSS completely. Even tenths of percent of clay-salt impurities remaining in the ore decrease the recovery of potassium chloride to the flotation concentrate and also require additional consumption of collecting agents (aliphatic amines) [16, 17]. In this regard, at the stage of sylvin flotation prior to entering collecting agents into the process, ore pulp is conditioned by depressors, which are adsorbed on the surface of CSS, change the nature of the interphase molecular interactions, thus increasing the selectivity of flotation. As a result, recovery of KC1 increases, content of CSS in the flotation concentrate decreases, with reducing consumption of collecting agents [8, 11, 12, 18, 19].

A large number of depressing agents (depressors) for flotation of potassium ores is known, of which organic agents should be noted: carboxymethylcellulose (CMC), modified urea-formaldehyde resins, modified starch, guar gum, epoxy resin, etc. [11, 12, 18]. These chemical compounds have proven to be effective CSS depressors. However, organic depressor molecules (e.g., CMC and starch) in solutions tend to form associates and supramolecular structures, the formation of which is promoted by increasing the agent concentration. Besides, ionogenic polymers, in particular CMC, are also characterized by the globulization of molecules and an increased intramolecular interaction [20–22]. As the concentration of organic depressor solutions increases, the viscosity of the solution increases and simultaneously the depressor properties deteriorate [21]. Therefore, commercial operations seek to use dilute solutions of depressors (e.g., CMC < 2 %), which can increase the depressing effect of the agents and reduce their specific consumption. However, the use of dilute depressor solutions leads to an additional introduction of water into the process, which causes losses of potassium chloride due to dissolution and accumulation of excessive alkali liquors.

Sonochemical pretreatment of highly concentrated organic depressor solutions is a promising way of solving the aforementioned problems [23]. Under the effect of ultrasonic cavitation, various physicochemical properties of colloidal system, such as viscosity, size of depressor molecules aggregates, electrokinetic potential, the adsorption value of depressor molecules on clay-salt impurities change, which, in turn, can increase the performance of flotation of potash ores [24, 25]. In the literary sources, there is practically no information concerning the effect of ultrasonic pretreatment of depressors on both the physicochemical properties of a depressor and on the flotation performance of a sylvinite ore.

The purpose of this study is to establish the effect of sonochemical pretreatment of depressors (CMC and starch) on the physicochemical properties of the depressor solutions, as well as on the performance of sylvinite flotation.

1. Research Materials and Methods

1.1. Flotation depressor (depressing agent)

Two types of organic depressors, carboxymethyl cellulose (degree of polymerization of 750–850) and soluble starch amylodextrin (C.P.) (hereinafter – starch) were used to study the effect of sonochemical treatment on a depressor in sylvin flotation. For the tests, 4 % aqueous solution of CMC and 4 % aqueous solution of starch were prepared at the solution temperatures of 30 °C.

In the process of sylvinite ore flotation beneficiation the depressor was added to the pulp before adding the emulsion of collector and frothing agent at the stage of sylvinite flotation. At the same time the specific consumption of CMC was 400 g/t ore, that of starch, 160 g/t ore [11].

1.2. Sonochemical treatment of depressor solution

Sonochemical treatment of the depressor solution was carried out using the ultrasonic unit shown in Fig. 1. As a source of ultrasonic vibrations, UZTA-0,8/22-OMU (series “Wave”) ultrasonic generator with piezoelectric oscillating system with developed radiating surface (made of titanium alloy) in the metal case and with forced air cooling was used.

The installation has a nominal operating frequency of 22 ± 1.65 kHz and the intensity of radiation not less than 3.5 W/cm^2. Electronic generator with timer and power regulator (40–100 %). At an ultrasonic impact at 100 % power, the total power consumption is 1600 VA, the active power input is 650 W, providing acting acoustic power of about 420 W. The depressor solution temperature was maintained by thermostat *3*. A depressor solution in an amount of 500 ml was placed into reactor 4, then treated by ultrasound at different levels of acoustic power (from 168 to 420 W in increments of 84) and exposure duration of 150 s. For comparison, control tests without sonochemical treatment under identical conditions were performed.

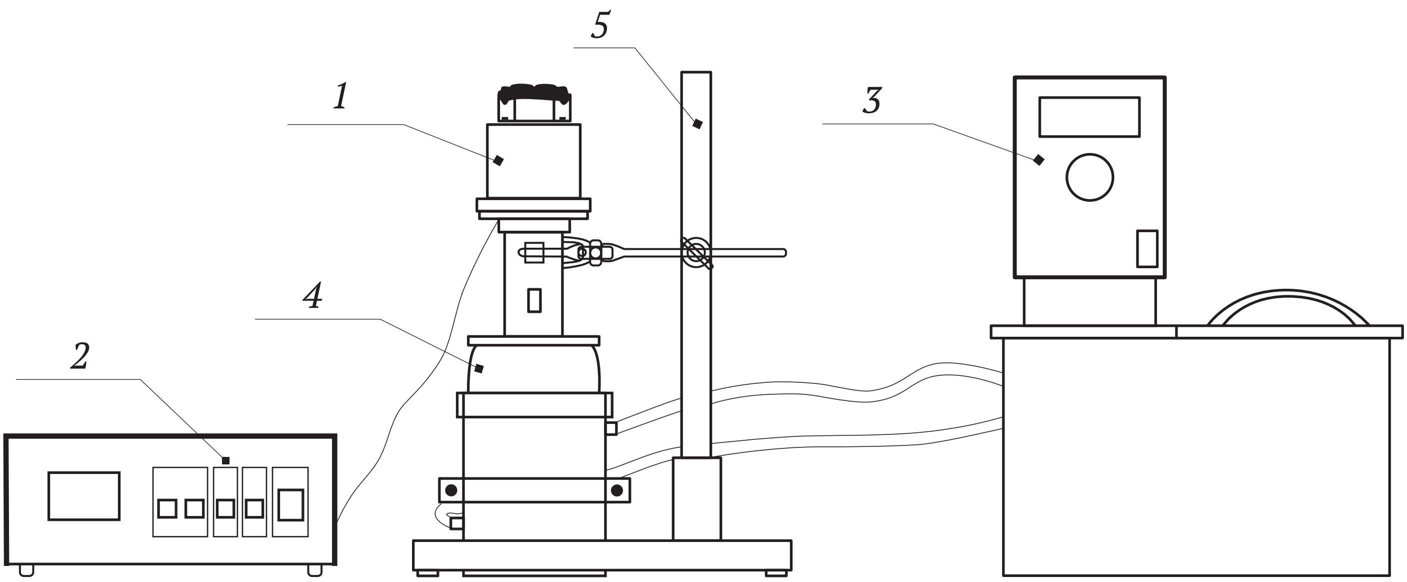

Fig. 1. Schematic representation of laboratory installation for sonochemical treatment of depressing agent: *1* – radiating element; *2* – ultrasonic generator; *3* – thermostat; *4* – reactor with a jacket; *5* – tripod

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1.3. Measurement of aggregate size and zeta potential of depressor solution

The aggregate size and zeta potential of CMC and starch depressors were measured by a Zetasizer Nano ZS laser instrument using the dynamic light scattering method with non-invasive backscattering technique. The viscosity values used to measure the aggregate size and zeta potential were taken equal to the reference values of water viscosity at a given temperature. The refractive index of the CMC solution is 1.515; that of the starch solution is 1.340.

Ten measurements of aggregate size in a sample volume were taken sequentially by the instrument, and then the results were averaged. There were three parallel measurements per sample.

1.4. Measurement of viscosity-temperature properties of the depressor solution

The dynamic viscosity of the ultrasonically treated and untreated depressor solutions was determined with an SV-10 AND vibro-viscosimeter. The technique for determining viscosity is based on changing the resonance frequency of oscillations in a liquid of different viscosity at a given known value of the solution density. The initial density of 4 % CMC solution at 30 °C was 1.02 kg/m^3; that of 4 % starch solution at 30 °C was 1.01 kg/m^3.

The solution temperature was measured by the vibro-viscosimeter's temperature sensors directly during the viscosity measurements. The temperature of the depressor solutions was changed using a laboratory thermostat.

The limit of tolerable relative error of the viscometer is ±3 %, the repeatability of viscosity measurement results, not more than 1 % (standard deviation).

1.5. Flotation tests

Dry sylvinite ore from flotation plant BKPRU-3 and sylvinite flotation feed (deslurried sylvinite ore) originating from flotation plant SKRU-3 of PJSC "Uralkali" of various chemical compositions (see Table 1) were used as raw materials for flotation production of potassium chloride in the tests.

Potassium chloride of "C.P." grade and sodium chloride of "C.P." grade were used for the preparation of saturated solutions used in the sylvin flotation study. The saturated solution was used only once.

Granulated primary amines (distilled) of C_{17}–C_{20} fraction and triethylene glycol C6H14O4 were used as a collector and frothing agent for sylvin flotation, respectively. To prepare the amine hydrochloride solution, solid stearylamine (pre-milled) with a concentration of 0.8 wt. % was added to distilled water and chemically pure (C.P.) hydrochloric acid in the amount 15 % higher than necessary to neutralize the stearylamine. The resulting solution was stirred and thermostatted at 70 °C for 90 min. Then the agent temperature was reduced to working temperature of 60 °C. Then the frothing agent was added to the amine hydrochloride solution in the amount of 30 % by weight of the dry collector.

The flotation tests were carried out using a "FML 3/240 FL" laboratory flotation machine. Dry initial ore was mixed with mother liquor at a L/S phase ratio of 2.5. The resulting pulp (ore suspension) under stirring was firstly added with an ultrasound treated or untreated depressor at a given consumption of the agent, then conditioned for 3 minutes, and then added with the "collector-frother" composition at a consumption of 65 g/t of ore, and then conditioned again for 1 minute. The laboratory flotation machine's cell was filled with ready ore suspension in the volume of 500 ml (the ore mass of 194 g, the mother liquor volume of 400 ml). The flotation machine was switched on with the impeller rotation velocity of 29 RPS and the air flow rate of 100 l/h. The duration of the flotation process was 6 min (three flotation cycles were performed per sample, the results of which were averaged). The collected froth product and flotation tail were filtered with a vacuum filter, then dried to constant weight. After drying, gravimetric analysis of the obtained products and tails was carried out and the content of potassium chloride in the flotation concentrate and the flotation tails was determined using a PFA 378 flame photometer. The analysis for the content of CSS in the flotation concentrate was carried out using an EDX-8100P "Shimadzu" energy dispersive X-ray fluorescence spectrometer with helium sparging. Such elements as Ca, Si, Al, Mg, S, and Fe were referred to CSS.

Table 1

Chemical composition of sylvinite ore originating from BKPRU-3 flotation plant and sylvin flotation feed from SKRU-3 flotation plant of PJSC "Uralkali"

Flotation plant	Weight percent of components, %					Fraction
	NaCl	KCl	Insol. res.*	$MgCl_2$	$CaSO_4$	
BKPRU-3	66.65	26.59	4.59	0.27	1.9	(−0.900 + 0.315) mm
SKRU-3	70.30	27.10	0.46	0.13	2.01	(−0.900 + 0.315) mm

* Insol. res. – insoluble residue.

2. Findings Discussion

2.1. Influence of sonochemical treatment of depressor on aggregate size

The results of the investigation of the effect of sonochemical treatment modes of depressor solutions on the size of aggregates (differential curves of the volume distribution of aggregates of CMC and starch molecules by size) are shown in Figs. 2 and 3.

As can be seen from Fig. 2, with increasing power of sonochemical influence the size of aggregates of molecules decreases: from 6 nm (without ultrasound treatment) to 4 nm (at acoustic power of ultrasound of 420 W). In concentrated solutions of CMC (above 1 %) exposed to ultrasound, breaking of bonds of macromolecules, which become loose and possess more expanded form, happens [26–28].

As can be seen from the analysis of the differential curves describing the volume distribution of starch

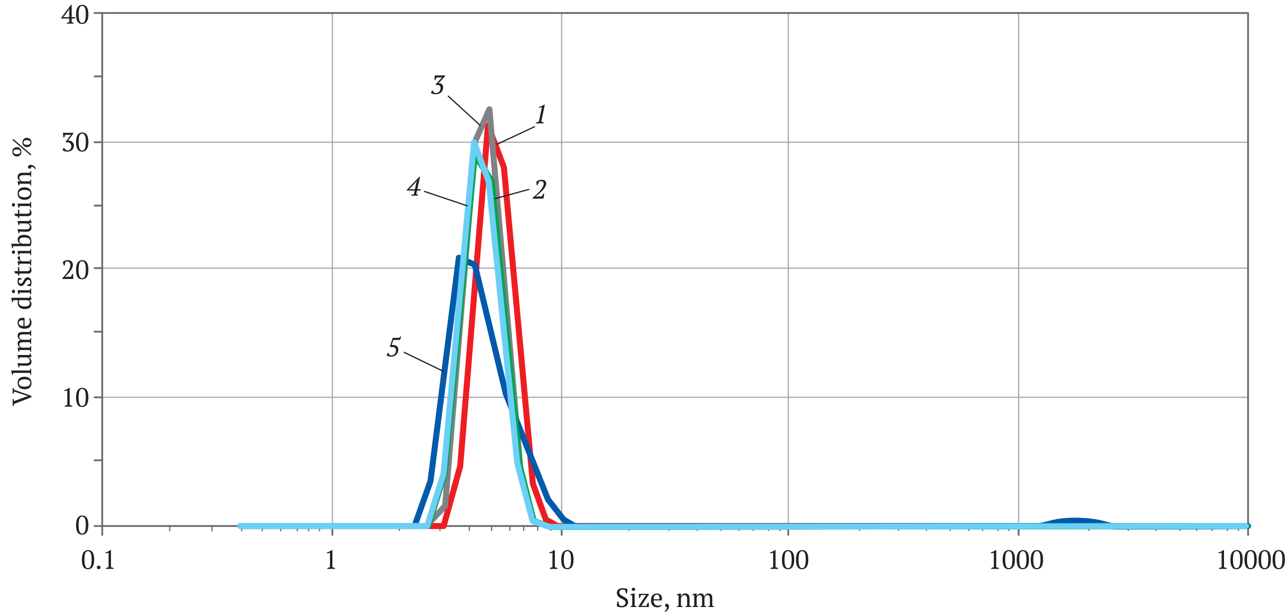

Fig. 2. Differential curves of volume distribution of aggregates of molecules in ultrasound-treated and non-treated CMC solution at duration of ultrasound exposure of 150 s:
1 (red) – without ultrasonic treatment; 2 (green) – 168 W; *3* (gray) – 252 W; *4* (turquoise) – 336 W; *5* (blue) – 420 W

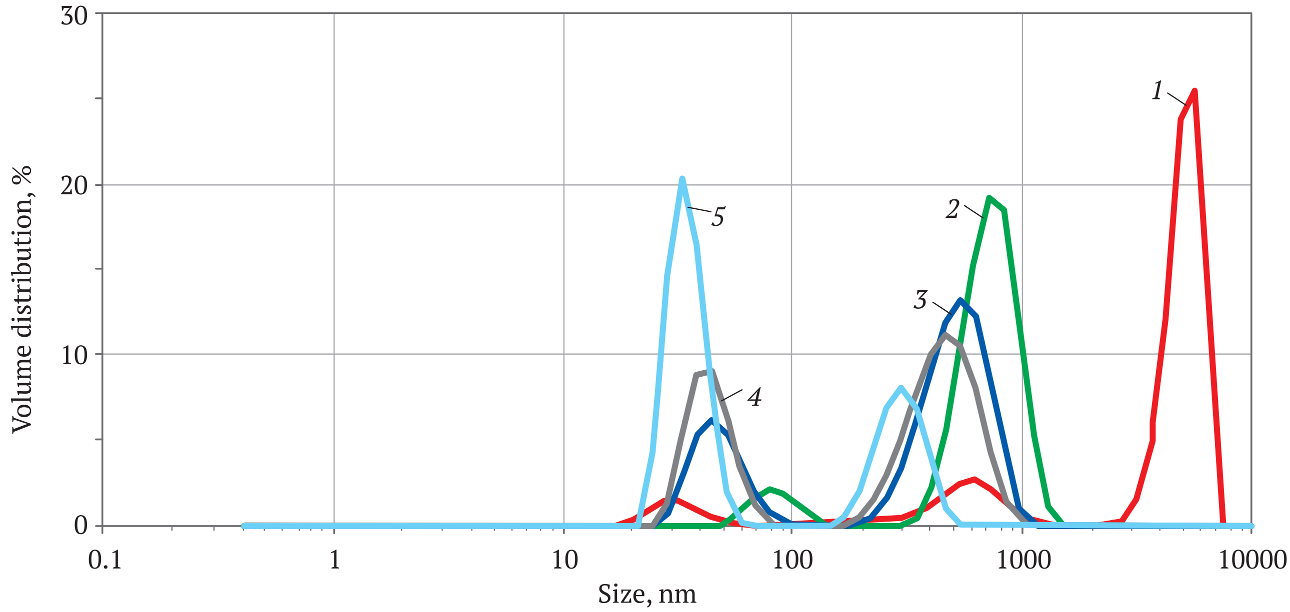

Fig. 3. Differential curves of volume distribution of aggregates of molecules in ultrasound-treated and non-treated starch solution at duration of ultrasound exposure of 150 s:
1 (red) – without ultrasonic treatment; *2* (green) – 168 W; *3* (blue) – 252 W; *4* (gray) – 336 W; *5* (turquoise) – 420 W

molecules aggregates, presented in Fig. 3, large starch aggregates without sonochemical treatment had different sizes: about 50, 900, and 8000 nm. Aggregates around 8000 nm in size were observed to dominate, as indicated by the volume distribution curve (curve *1*). With gradual increasing the acoustic power of ultrasonic treatment, the distribution curves of starch aggregates shifted toward decreasing the aggregate size, and the height of the volume distribution peaks also decreased. At the same time, after ultrasonic treatment, the peak of aggregate distribution in the area of 8000 nm disappeared. At acoustic power of 420 W the maximum decreasing the aggregate size to 60 nm with volume distribution of 20 % and 600 nm with volume distribution less than 10 % is observed. Thus, after exposure to ultrasound at maximum power, the size of starch aggregates decreased by more than 133 times: from 8000 nm to 60 nm.

2.2. Effect of ultrasonic treatment of depressor on the change in electrokinetic potential

The results of the studies of the effect of sonochemical treatment of depressors solutions on zeta-potential are shown in Fig. 4.

As can be seen from Fig. 4 (curve *1*), the values of zeta potential of the CMC solution gradually shifts to the area of negative values with increasing sonochemical treatment power. In this case, the maximum negative zeta potential value of -35.85±1.79 mV is observed at an ultrasonic power of 420 W. It should be noted that CMC belongs to the group of ionogenic anionic depressors, having carboxyl group in its composition, which imparts to this agent a negative value of electrokinetic potential. As noted above (see section 2.1), ultrasound breaks the internal bonds of the CMC supramolecular structures that leads to forming expanded forms and growing anionic structures, which shift the zeta potential to the area of negative values [20, 24]. Since sonochemical treatment of CMC solution reduces zeta potential of this depressor solution, the sorption of CMC aggregates on the surface of positively charged slurry particles, such as hematite, should increase, due to which the hydrophilicity of these particles may increase.

Analysis of Fig. 4 (curve *2*) shows that sonochemical treatment at any acoustic power insignificantly affects the zeta potential of starch aggregates. At the same time, the electrokinetic potential at all acoustic powers of sonochemical treatment is close to 0. The peculiarities revealed are explained by the fact that starch belongs to the group of non-ionogenic organic depressors that do not carry a charge [29, 30]. The fixation of this depressor on the surface of silicate slurry minerals, such as quartz, occurs through the formation of hydrogen bonds, where a large number of polar groups of each depressor molecule is involved, thus achieving a strong bond of the depressor with the mineral [31, 32]. It is possible that under the influence of ultrasound on the starch solution the starch aggregates, as in the case of CMC, become loose, thereby increasing the number of active polar groups, which are more firmly bound to the surface of the slurry minerals and lead to an increase in its hydrophilicity.

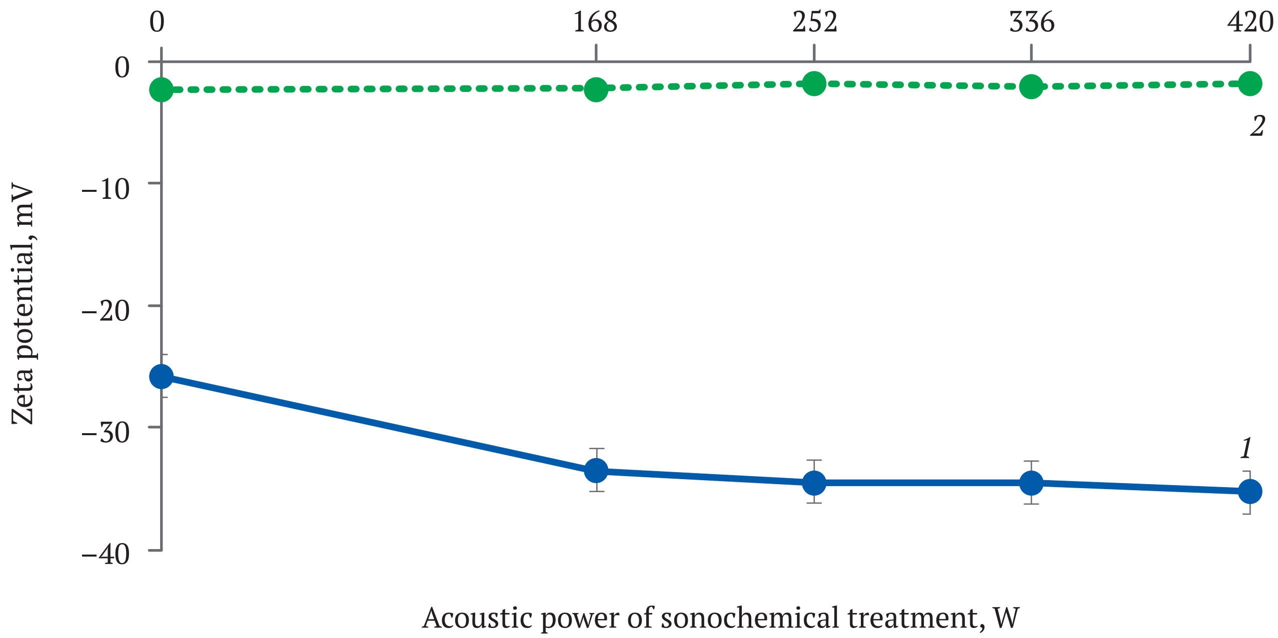

Fig. 4. Effect of ultrasonic treatment of depressor on the change in electrokinetic potential:
1 – CMC solution; *2* – starch solution

2.3. Influence of sonochemical treatment on viscosity-temperature properties of depressor

The effect of ultrasonic treatment of CMC and starch solutions on the change in dynamic viscosity and temperature is shown in Table 2.

The analysis of Table 2 shows that with increasing acoustic power of the agents sonochemical treatment, the dynamic viscosity of the solutions decreases, while their temperature increases. The maximum decrease in the dynamic viscosity and increase in the temperature of CMC solution are observed at sonochemical treatment acoustic power of 420 W, and these parameters reach 5.05 ± 0.05 mPa-s and 38 °C, respectively; the ultrasonic treatment of starch solution at the same acoustic power decreases the viscosity to 2.66 ± 0.03 mPa-s, while the temperature of the solution increases to 41 °C. Sonochemical treatment had the greatest effect on the starch solution, in which the dynamic viscosity decreased by 3.3 times when the maximum acoustic power of ultrasound was applied.

At the same time, as shown in Table 2, increasing the temperature of the agent solutions without using sonochemical treatment insignificantly decreased the dynamic viscosity of the solutions, indicating that the greatest contribution to the change in viscosity was made by ultrasonic treatment. It should be taken into account that sonochemical treatment generates and subsequently collapses gas bubbles in the liquid, which locally increases pressure and temperature [21, 33, 34]. This local change in temperature raises the temperature of the entire solution and the change in pressure causes the colloidal solution aggregates to disperse, causing the viscosity of the medium to decrease.

2.4. Effect of sonochemical depressor treatment on the clay-salt slurry content in concentrate and KCl recovery

In the tests on flotation separation of sylvinite components, the effect of sonochemical pretreatment of depressing agents (CMC and starch) on the recovery of KCl and the content of clay-salt slurry in the concentrate was studied. In these studies, we used sylvinite ore originating from BKPRU-3 flotation plant with a high content of insoluble residue (the initial composition of the ore is presented in Table 1). The results are shown in Table 3.

It is clear from Table 3 that the application of the non-treated ultrasound CMC solution reduces the content of clay-salt slurry in the concentrate to 22.84 ± 0.46 wt. % and increases the potassium chloride recovery by 1.44 % as compared to the test results where no depressor was used. Applying sonochemical treatment of CMC solution at an acoustic power of 168–252 W further increases KCl recovery and reduces the content of clay-salt slurry in the flotation concentrate (tests 3–4). At the same time the best results (increase of KCl recovery and decrease

Table 2

Effect of ultrasonic treatment and increasing temperature of CMC and starch solutions on dynamic viscosity

Depressor type	Acoustic power, W	Solution temperature, °C	Solution dynamic viscosity, mPa-s	Solution temperature, °C	Solution dynamic viscosity, mPa-s
	with ultrasonic treatment			without ultrasonic treatment	
CMC	0	30	9.01 ± 0.09	30	9.01 ± 0.09
	168	32	7.27 ± 0.07	32	8.74 ± 0.09
	252	35	5.70 ± 0.06	35	8.44 ± 0.08
	336	37	5.18 ± 0.05	37	8.24 ± 0.08
	420	38	5.05 ± 0.05	38	8.14 ± 0.08
Starch	0	30	8.87 ± 0.09	30	8.87 ± 0.09
	168	32	4.18 ± 0.04	32	8.27 ± 0.08
	252	35	3.33 ± 0.03	35	8.07 ± 0.08
	336	38	2.92 ± 0.03	38	7.78 ± 0.08
		41	2.66 ± 0.03	41	7.49 ± 0.07

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of the slurry content) are observed at acoustic power of ultrasound of 252 W. However, further increase in the acoustic power of sonochemical treatment up to 336–420 W (tests 5–6) reduces the performance of the ultrasonic treated depressor. Similar regularities are observed when using ultrasound-treated starch (tests 8–11). The optimum acoustic power at which the maximum KCl recovery and the minimum slurry content in the flotation concentrate are observed is 252 W.

The positive effect of sonochemical pretreatment of depressors on the flotation performance is primarily due to the effect of ultrasonic cavitation, which contributes to the dispersion of large aggregates of CMC and starch (see sections 2.1 and 2.2), thereby increasing the number of active polar groups, which probably are more firmly bound with the surface of slurry particles and lead to an increase in their hydrophilicity, thereby improving the sylvin flotation performance.

Decreasing sylvin recovery and increasing the content of slurry in the concentrate when using high-power ultrasound-treated depressors are most likely connected with the processes of degradation and oxidation of organic macromolecules of CMC and starch, which thus lose their activity [35–37].

2.5. Applying sonochemical pretreatment to reduce depressor consumption

In order to confirm the possibility of reducing sylvin flotation depressor consumption, laboratory flotation tests were carried out, the results of which are provided in Table 4. Starch was chosen as the depressor since it is more efficient than KMC in increasing KCl recovery (see section 2.4). The depres-

Table 3

The effect of depressor sonochemical pretreatment on clay-salt content in flotation concentrate and KCl recovery

Test No.	Depressor	Acoustic power, W	Content of clay-salt slurry in concentrate, mass %	KCl recovery, %
1	Without depressor	Without sonochemical treatment	25.70 ± 0.51	23.07 ± 0.05
2	CMC	Without sonochemical treatment	22.84 ± 0.46	24.51 ± 0.32
3		168	21.85 ± 0.44	25.36 ± 1.11
4		252	9.57 ± 0.19	29.68 ± 2.25
5		336	11.41 ± 0.23	28.16 ± 0.23
6		420	17.98 ± 0.36	25.26 ± 1.01
7	Starch	Without sonochemical treatment	12.98 ± 0.26	26.63 ± 1.24
8		168	9.14 ± 0.18	28.86 ± 1.27
9		252	7.02 ± 0.14	30.29 ± 0.05
10		336	26.19 ± 0.52	20.76 ± 0.86
11			31.85 ± 0.64	19.79 ± 2.08

Table 4

Effect of ultrasound-treated depressor consumption on KCl recovery at acoustic ultrasound power of 252 W and exposure time of 150 s

Depressor consumption, g/t ore	160*	160	150	140	130	120	110	100
KCl recovery, %	55.72 ± 0.25	62.05 ± 2.02	60.31 ± 0.14	59.82 ± 0.99	59.32 ± 1.69	57.92 ± 3.78	54.84 ± 0.68	52.02 ± 0.23

* The use of ultrasonically-untreated depressor solution.

sor consumption was reduced from 160 to 100 g/t ore in increments of 10 and only starch solution was sonochemically treated. The critical consumption of the depressor was considered to be the value after which the sylvin recovery was decreased by the next value as compared with the use of ultrasonically-untreated depressor (marked "160*"). In these studies we used sylvin flotation feed of SKRU-3 flotation plant with low insoluble residue content, the composition of which is shown above in Table 1.

The analysis of data of Table 4 reveals that sonochemical pretreatment of the starch solution with consumption of 160 g/t ore increases the recovery of potassium chloride in comparison with the ultrasonically-untreated depressor (160*). Decreasing the consumption of the ultrasonically treated depressor to 120 g/t ore reduces the recovery of KCl, while it remains higher by 2.2 % as compared to the KCl recovery in the test, in which the depressor was not treated with ultrasound. Further reduction of the depressor consumption to 110–100 g/t decreases the KCl recovery below the critical level (160*) by a few percent.

Thus, the use of sonochemical depressor pretreatment not only increases KCl recovery in the sylvin flotation process, but also reduces depressor consumption. The obtained results should be tested under industrial conditions.

Conclusion

The effect of sonochemical pretreatment of depressor reagents, CMC and starch, on dynamic viscosity, molecule aggregate size, electrokinetic potential of these agents solutions and sylvin flotation performance has been studied. It was found that the sonochemical treatment of depressor solutions decreases the size of CMC molecule aggregates from 6 to 4 nm and that of aggregates of starch molecules from 8000 to 60–600 nm. It was found that sonochemical treatment of anionic CMC solution shifts the zeta potential to the negative area with increasing acoustic power of ultrasound, but has no effect on the electrokinetic potential of nonionic starch solution. It was also found that sonochemical pretreatment of CMC and starch solutions reduces the dynamic viscosity of the agents solutions. It was revealed that sonochemical pretreatment of depressors at acoustic power of 168 and 252 W increases the recovery of KCl and reduces the content of slurry in the flotation concentrate. In addition, the possibility of reducing the consumption of the ultrasonicaly treated depressor was demonstrated. Thus, sonochemical pretreatment of depressors improves the sylvinite flotation performance due to dispersion of the agent molecules aggregates and changes in physical and chemical properties of the depressors. This can be used in the process of flotation beneficiation of sylvinite ores on commercial scale after performing pilot-plant tests.

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SAFETY IN MINING AND PROCESSING INDUSTRY AND ENVIRONMENTAL PROTECTION

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Higher rank aerological risks in coal mines

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Abstract
The steady trend of complication of mining and geological factors in underground coal mining and at the same time the processes of mining intensification cause growth of dynamic manifestations of natural factors of mining, such as sudden coal and gas outbursts, rock bursts, rock collapses, leading to gas and dust explosions and fires. This requires developing the models of different phenomena manifestation risks, which enable improving the process safety of a mining enterprise. In this study, based on the methodology of aerological risk assessment in coal mines, a structural analysis of aerological risks was carried out. The criteria of hazard of mining-geological and mine engineering factors and vulnerability of schemes and methods of ventilation, ventilation facilities, and main fans were developed. A hierarchical structure of aerological risks of higher ranks was developed. The presented risk structure allows determining the area of superposition of hazards of coal mining and vulnerability of ventilation systems for each mine and its individual facilities, as well as quantifying these areas in the form of aerological risks. The ranges of aerological risk values of higher ranks for super-category mines and mines hazardous by sudden coal and gas outbursts for different ventilation modes were established. The presented methodology enables forecasting and reducing aerological risks in course of designing, operation, liquidation, and conservation of coal mines.

Keywords
coal mine, aerological safety methodology, hierarchical risk structure, aerological risk ranks, methane, coal dust, hazard criteria, vulnerability of ventilation systems

For citation
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ТЕХНОЛОГИЧЕСКАЯ БЕЗОПАСНОСТЬ В МИНЕРАЛЬНО-СЫРЬЕВОМ КОМПЛЕКСЕ И ОХРАНА ОКРУЖАЮЩЕЙ СРЕДЫ

Научная статья

Аэрологические риски высших рангов в угольных шахтах

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Аннотация
Устойчивая тенденция перехода к осложнению горно-геологических факторов при подземной добыче угля и одновременно при этом процессы повышения интенсификации горных работ вызывают рост динамических проявлений природных факторов горного производства, таких как внезапные выбросы угля и газа, горные удары, обрушения пород, приводящие к взрывам газа и пыли, пожарам. Это

приводит к необходимости разрабатывать модели рисков проявления разных явлений, что позволяет повысить технологическую безопасность горного предприятия. В представленном исследовании на основе методологии оценки аэрологических рисков в угольных шахтах проведен структурный анализ аэрологических рисков. Сформированы критерии опасности горно-геологических и горнотехнических факторов и уязвимости схем и способов вентиляции, а также вентиляционных сооружений и вентиляторов главного проветривания. Разработана иерархическая структура аэрологических рисков высших рангов. Представленная структура рисков позволяет для каждой шахты и отдельных ее объектов определить область пересечения опасных факторов угледобычи и уязвимости систем вентиляции, а также количественно оценить эти области в виде аэрологических рисков. Установлены диапазоны значений аэрологического риска высших рангов для сверхкатегорийных шахт и шахт, опасных по внезапным выбросам угля и газа, для разных вентиляционных режимов. Представленная методология позволяет осуществлять прогнозирование и снижение аэрологических рисков при проектировании, эксплуатации, ликвидации и консервации угольных шахт.

Ключевые слова

угольная шахта, методология обеспечения аэрологической безопасности, иерархическая структура рисков, ранги аэрологических рисков, метан, угольная пыль, критерии опасности, уязвимость схем вентиляции

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Introduction

The problem of ensuring aerological safety of coal mines has a complex, systemic nature. The solution of the problem requires the effectiveness of implementation of an interrelated set of technical, technological, engineering, and information systems, production activities, and skilled personnel, aimed at reducing not only the level of aerological risk, but also other types of risk, such as geotechnical, geomechanical, hydrogeological, organizational, and technical [1–3].

The main hazards in coal mines are dust and gas, they lead to the most severe types of accidents, gas and dust explosions and fires [4, 5]. In recent years in the Russian Federation and abroad, an intensive search for new, more effective means and methods of explosion protection of mine workings, meeting modern requirements and technical capabilities is carried out [6–8].

As a result of these studies, the following areas have been studied in greater depth with the use of numerical modeling:

– methane distribution in areas of intensive mining in coal mines [9–11];

– properties of multicomponent explosive gas-air mixtures in a mine atmosphere [12];

– processes of coal dust deposition in mine workings [13, 14].

In the current conditions of high loads on the mining faces, an intensive in-situ degassing of mines is carried out to ensure the safety of high-productive faces, as exemplified by the Mine named after S.M. Kirov (Leninsk-Kuznetsky) [15]. In [16, 17] successful solutions for degassing of mine working fields and reduction of dust formation in longwall faces are presented.

In the conditions of development of high-gas-bearing coal seams, hazardous by the dust factor, it is impossible to ensure aerological safety without applying degassing and technologies of dedusting of coal seams [18, 19]. However, ventilation is still the primary method for gas and dust hazard control in coal mines. At a sudden stop of the main fan in fiery mines, if turning on the standby fan is impossible, all work in the mine areas must be stopped, electrical equipment should be de-energized, all personnel should be relocated to the air shaft in 30 minutes, and at faults, which require a long time to fix, the personnel should be delivered to the surface. Therefore, for effective selection of air-supply schemes in coal mines, the issues of evaluation and analysis of aerodynamic parameters of air streams require continuous research [20–22]. It is necessary to calculate the stability of air streams in mine workings based on quantitative parameters, ventilation directions, and the factor of thermal drop of ventilation pressure [23]. Aspects of aerological safety, based on quantitative assessments of accident risks, find their application in the implementation of the projects of digital transformation and intellectualization of mining systems [24, 25]. This, in turn, determines the promising directions of coal mines technological structure development [26, 27], allows developing evolutionary models of the safety system of coal mines based on multifactor modeling, including with the use of intelligent algorithms and methods [28, 29].

Methodology for aerological risk assessment

In order to successfully solve many design and production issues related to ensuring aerological safety of coal mines at the proper level, it is necessary to analyze and process huge flows of structured information, which are interconnected hierarchically and represent a kind of information architecture of aerological safety. For this architecture, hazard criteria for the system as a whole and the vulnerability of its elements should be prescribed, in accordance with which engineering solutions to prevent the impact of hazardous mining and geological and mine engineering factors of coal mining should be developed. The ultimate goal of building an aerological safety architecture is to quantify aerological safety and identify ways to improve it.

One of the quantitative characteristics of aerological safety are aerological risks, which express a probabilistic measure of the hazard of accidents due to unsatisfactory composition of the mine atmosphere, occurring in ventilation schemes of a certain vulnerability. As a result of this research, hazard and vulnerability criteria were formed in the structure of aerological risks, covering the entire aerological safety architecture. This made it possible to combine all the studies conducted and quantify both the aerological safety of the mine as a whole and its individual components.

The hierarchical structure of aerological risks was created from particulars to generals according to "the bottom-up approach" from the individual facilities of the mine to the mine as a whole. For this purpose, the entire mine was divided into three areas based on the level of operation of its facilities. First, the concept of aerological risks was developed for working areas and development workings, which took the lower position in the ranking system and were defined as rank III risks. Aerological risks of failures capable to lead to accidents within mine wings took the middle position in the ranking structure and were defined as rank II risks. Aerological risks of failures capable to lead to accidents of the entire mine scale took the top position in the ranking structure and were defined as rank I risks.

Aerological risks of rank III were investigated in earlier works of the author, and based on these studies findings, the following was developed:

– the hierarchical structure of risks of this rank;

– the hazard criteria of factors and vulnerability of ventilation schemes at the level of areas and development workings;

– the methods of aerological risk assessment for working areas and development workings;

– the methodology for calculating the predicted values of risk when using measures to manage gas release through degassing of high-gas-bearing coal seams, hazardous in terms of dust explosions;

as well as:

– quantitative comparison of gas hazard risks of mine workings with different ventilation schemes was obtained; the influence of mine workings aerodynamic ageing on the risks of area and permanent mine openings with different methods of their protection was assessed;

– values of rank III aerological risks were calculated for a number of mines in the Kuznetsk Basin.

Since the structure of rank III risks has already been given in previous publications of the author, it is necessary to focus in more detail on the structure of risks of ranks II and I.

Hazard and vulnerability indicators in the structure of risk ranking I and II

The basic scheme of the structures of all ranks is the same, almost the same set of mining hazards is used, but the areas of impact of these factors at each level are different. This makes it necessary to establish different types and levels of ventilation vulnerability and, correspondingly, different levels of negative consequences of ventilation failures. The main hazard indicators in the structure of aerological risks of all ranks are gas and dust hazards as well as rock temperature. Assessment of the explosiveness of coal mines includes an assessment of the explosive properties of multicomponent gas-dust-air mixtures containing heavy hydrocarbons in the mine atmosphere. For rank II risks, the most hazardous layer of a mine wing is selected, while for rank I risks, the most hazardous seam of the mine is selected.

Aerological risk of rank I $R_{\alpha m}$ is calculated by the formula

$$R_{\alpha m} = \lambda_m v_m, \quad (1)$$

where λ_m is accident hazard factor for a mine; v_m is mine ventilation vulnerability factor;

$$\lambda_m = (\delta_{dm} q_{dm} + \delta_{gm} q_{gm})\lambda_0, \quad (2)$$

where δ_{dm} is factor of significance of the dust factor for a mine; q_{dm} is value of the mine hazard indicator code based on specific dust emission; δ_{gm} is factor of significance of the gas factor for a mine; q_{gm} is value of the mine hazard indicator code based on relative gas content; λ_0 is normalizing multiplier;

$$v_m = (\varphi_{vs}\alpha_{vs} + \varphi_{vm}\alpha_{vm} + \varphi_{mf}\alpha_{mf})v_0, \quad (3)$$

where φ_{vs} is vulnerability significance factor of the mine ventilation scheme; α_{vs} is vulnerability code value of the mine ventilation scheme; φ_{vm} is vulnerability significance factor of the mine ventilation method; α_{vm} is vulnerability code value of the mine ventilation method; φ_{mf} is vulnerability significance factor of the main mine fans; α_{mf} is vulnerability code value of the main mine fans; v_0 is normalizing multiplier.

By decomposing the values of the indicators in formula (3), we obtain:

$$\varphi_{vs} = (\varphi_{spd}\alpha_{spd} + \varphi_{di}\alpha_{di} + \varphi_{vsi}\alpha_{vsi})v_1, \quad (4)$$

where φ_{spd} is factor of significance of the influence of the mine ventilating pressure drop value on the vulnerability of the mine ventilation scheme; α_{spd} is vulnerability code value of the mine ventilation scheme depending on the value of the mine ventilating pressure drop; φ_{di} is significance of the degree of influence of direction of fresh air and return air on air leaks; α_{di} is vulnerability code value of the mine ventilation scheme depending on the degree of influence of direction of fresh air and return air on air leaks; φ_{vsi} is significance of the influence of ventilation stability on the vulnerability of the scheme; α_{vsi} is vulnerability code value of the mine ventilation scheme depending on the mine ventilation stability; v_1 is normalizing multiplier;

$$\varphi_{vm} = \varphi_{vmgh}\alpha_{vmgh}v_2, \quad (5)$$

where φ_{vmgh} is factor of significance of the degree of influence of the ventilation method on the workings gas hazard at a sudden stop of the main fan; α_{vmgh} is value of the vulnerability code of the degree of influence of the ventilation method on the workings gas hazard at a sudden stop of the main fan; v_2 is normalizing multiplier;

$$\varphi_{mf} = (\varphi_{mfs}\alpha_{mfs} + \varphi_{mfp}\alpha_{mfp} + \varphi_{mfl}\alpha_{mfl})v_3, \quad (6)$$

where φ_{mfs} is factor of significance of the degree of influence of the stability of the joint operation of the main fans; α_{mfs} is value of the code of the degree of influence of the stability of the joint operation of the main fans; φ_{mfp} is factor of significance of the degree of the mine provision with air; α_{mfp} is value of the code of significance of the degree of the mine provision with air; φ_{mfl} is factor of significance of the magnitude of the external air leakage; α_{mfl} is value of the code of significance of the magnitude of the external air leakage; v_3 is normalizing multiplier.

The presented indicators of hazard and vulnerability in the structure of the risks of rank I are hierarchically linked in the functional system shown in Fig. 1.

The vulnerability of ventilation at the rank I risk level includes: the vulnerability of mine ventilation schemes and methods and the vulnerability of main fans. The vulnerability of mine ventilation schemes is determined by: the magnitude of the mine ventilating pressure drop, the degree of influence of the fresh air and return air movement directions on air leakage; the stability of mine ventilation. The vulnerability of ventilation methods at the level of rank I risks includes: the degree of influence of the method of ventilation on the workings gas hazard in the case of stopping the main fans.

The vulnerability of main fans is determined by: the stability of joint operation of main fans, the degree of the mine provision with air, the magnitude of external air leakage.

The vulnerability of ventilation at the rank II risk level includes: the vulnerability of schemes and methods of ventilation of mine wings and the vulnerability of ventilation facilities. In turn, the vulnerability of ventilation schemes of mine wings is determined by: the magnitude of the ventilating pressure drop in haulage and ventilation main drifts, which depends on the type of drift (field, seam), method of protection (pillar-pillar, pillar-mined-out space, mined-out space-mined-out space); the degree of influence of the direction of fresh air and return air motion on air leakage; stability of ventilation of a mine wing; the value of thermal drop of ventilation pressure in inclined workings.

The vulnerability of ventilation methods at the level of rank II risks includes: the degree of influence of the method of ventilation on the workings gas hazard in the case of stopping the main fans. The vulnerability of ventilation facilities is determined by the degree of their effect on the stability of ventilation.

Aerological risk of rank II is calculated by the following formula:

$$R_{\alpha mw} = \lambda_{mw}v_{mw}, \quad (7)$$

where λ_{mw} is the accident hazard factor for a mine wing; v_{mw} is the vulnerability factor of a mine wing ventilation;

$$\lambda_{mw} = (\delta_{dmw}q_{dmw} + \delta_{gmw}q_{gmw})\lambda_{0mw}, \quad (8)$$

where δ_{dmw} is factor of significance of the dust factor for a mine wing; q_{dmw} is the value of the mine seam hazard indicator code based on specific dust release for a mine wing; δ_{gmw} is factor of significance of the gas factor for a mine wing; q_{gmw} is the value of the mine seam hazard indicator code based on relative gas content for a mine wing; λ_{0mw} is normalizing multiplier;

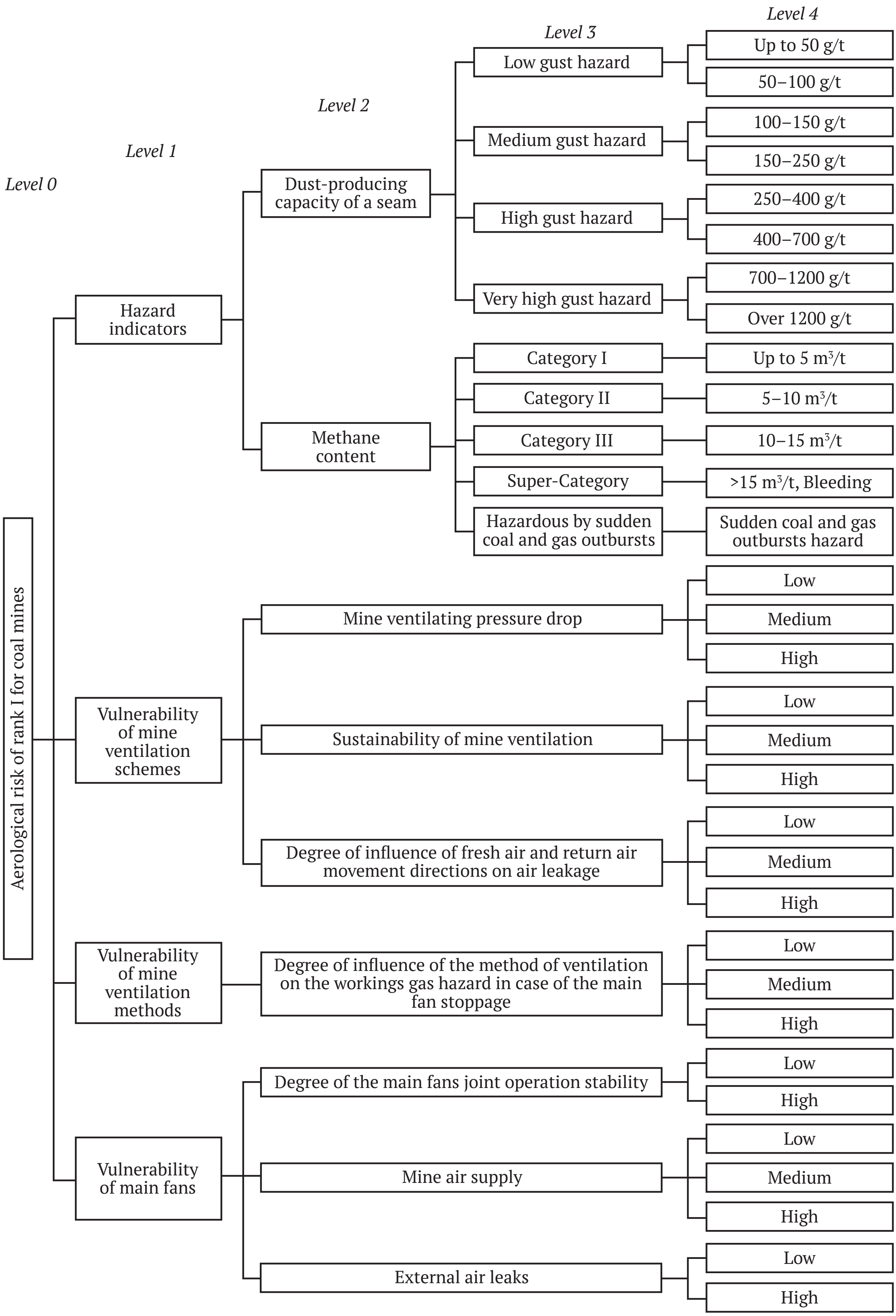

Fig. 1. Hierarchical structure of rank I aerological risks

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$$v_{mw} = (\varphi_{wvs}\alpha_{wvs} + \varphi_{wvm}\alpha_{wvm} + \varphi_{mwvf}\alpha_{mwvf})v_{1k}, \quad (9)$$

where φ_{wvs} is vulnerability significance factor of a mine wing ventilation scheme; α_{wvs} is vulnerability code value of a mine wing ventilation scheme; φ_{wvm} is vulnerability significance factor of a mine wing ventilation method; α_{wvm} is vulnerability code value of a mine wing ventilation method; φ_{mwvf} кis vulnerability significance factor of a mine wing ventilation facilities; α_{mwvf} is vulnerability code value of a mine wing ventilation facilities; v_{1k} is normalizing multiplier.

By decomposing the values of the indicators in formula (9), we obtain:

$$\varphi_{wvs} = (\varphi_{pds}\alpha_{pds} + \varphi_{mwvc}\alpha_{mwvc} + \varphi_{mwvs}\alpha_{mwvs} + \varphi_{ivptd}\alpha_{ivptd})v_{2k}, \quad (10)$$

where φ_{pds} is significance factor of the effect of the magnitude of ventilating pressure drop in haulage and ventilation main drifts; α_{pds} is vulnerability code value of the mine wing ventilation scheme depending on the magnitude of ventilating pressure drop in haulage and ventilation main drifts; φ_{mwdv} is significance factor of the degree of influence of the direction of fresh air and return air movement on air leaks; α_{mwdv} is vulnerability code value of a mine's wing ventilation scheme depending on the degree of influence of the direction of fresh air and return air movement on air leaks; φ_{mwvs} is significance factor of the influence of ventilation stability on the vulnerability of the ventilation scheme of a mine wing; α_{mwvs} is significance code value of the vulnerability of the ventilation scheme of the mine wing, depending on the stability of ventilation; φ_{ivptd} is significance factor of the magnitude of thermal drop of ventilation pressure in inclined mine workings; α_{ivptd} is significance code value of the magnitude of thermal drop of ventilation pressure in inclined mine workings; v_{2k} is normalizing multiplier;

$$\varphi_{vmw} = \varphi_{vmwgh}\alpha_{vmwgh}v_{3k}, \quad (11)$$

where φ_{vmwgh} is factor of significance of the degree of influence of a mine's wing ventilation method on the workings gas hazard at a sudden stop of the main fan; α_{vmwgh} is value of the vulnerability code of the degree of influence of a mine's wing ventilation method on the workings gas hazard at a sudden stop of the main fan; v_{3k} is normalizing multiplier;

$$\varphi_{vfs} = \varphi_{vfs}\alpha_{vfs}v_{4k}, \quad (12)$$

where φ_{vfs} is factor of significance of the degree of influence of ventilation facilities on the stability of ventilation; α_{vfs} is the value of the code of the degree of influence of ventilation facilities on the stability of ventilation; v_{4k} is normalizing multiplier.

The presented indicators of hazard and vulnerability in the structure of rank II risks are hierarchically represented in the form of a functional diagram in Fig. 2.

Thus, the presented methodology of aerological safety architecture design, including aerological risk assessments, enables quantifying the effectiveness of various methods of mine ventilation improvement.

Research Findings

A well-known approach of obtaining normalizing factors characterizing the share of vulnerability (aerological risk) of schemes and methods of mine (mine wing) ventilation as compared with the most adverse situation (taken as a unit) was taken as a basis for quantitative assessment of hazard, vulnerability, aerological risk. For a mine it comprises a central duplex ventilation scheme, blow-in method of ventilation, exacerbated by unfavorable conditions: the scheme with low degree of stability (tilting of the ventilation stream occurs at normal operation of the mine — the 3rd category of stability), a great mine ventilating pressure drop, a large degree of influence of the direction of fresh air and return air movement on air leakage, a large degree of influence of the ventilation method on gas hazard (content) in workings when the main fans stop, low mine provision with air, high external air leaks, etc.

Table 1 shows ranges of values of aerological risk of rank I for super-category mines and mines hazardous by sudden coal and gas outbursts for different ventilation modes The first figure of the range of the risk values reflects the most favorable conditions: the least dust emission, no diagonals in the ventilation network, direct-flow scheme of air movement, low mine ventilating pressure drop, stable joint work of main fans, the availability of air supply reserve in a mine, low external leaks, etc.

Analysis of the calculated data shows that while the risks for different ventilation schemes and methods increase from the best to the worst conditions in 2.1 times (0.152/0.078), the value of the risk depends on the values of ventilation parameters to much greater extent and the risk increases in 6.8 times (0.535/0.078) from the best to the worst conditions. A similar dependence was identified for rank II risks (Table 2).

It should be noted that the methodology makes it possible to highlight the most significant components (ventilation indicators) from the risk structure and develop engineering measures to reduce aerological risks and increase the efficiency of aerological safety.

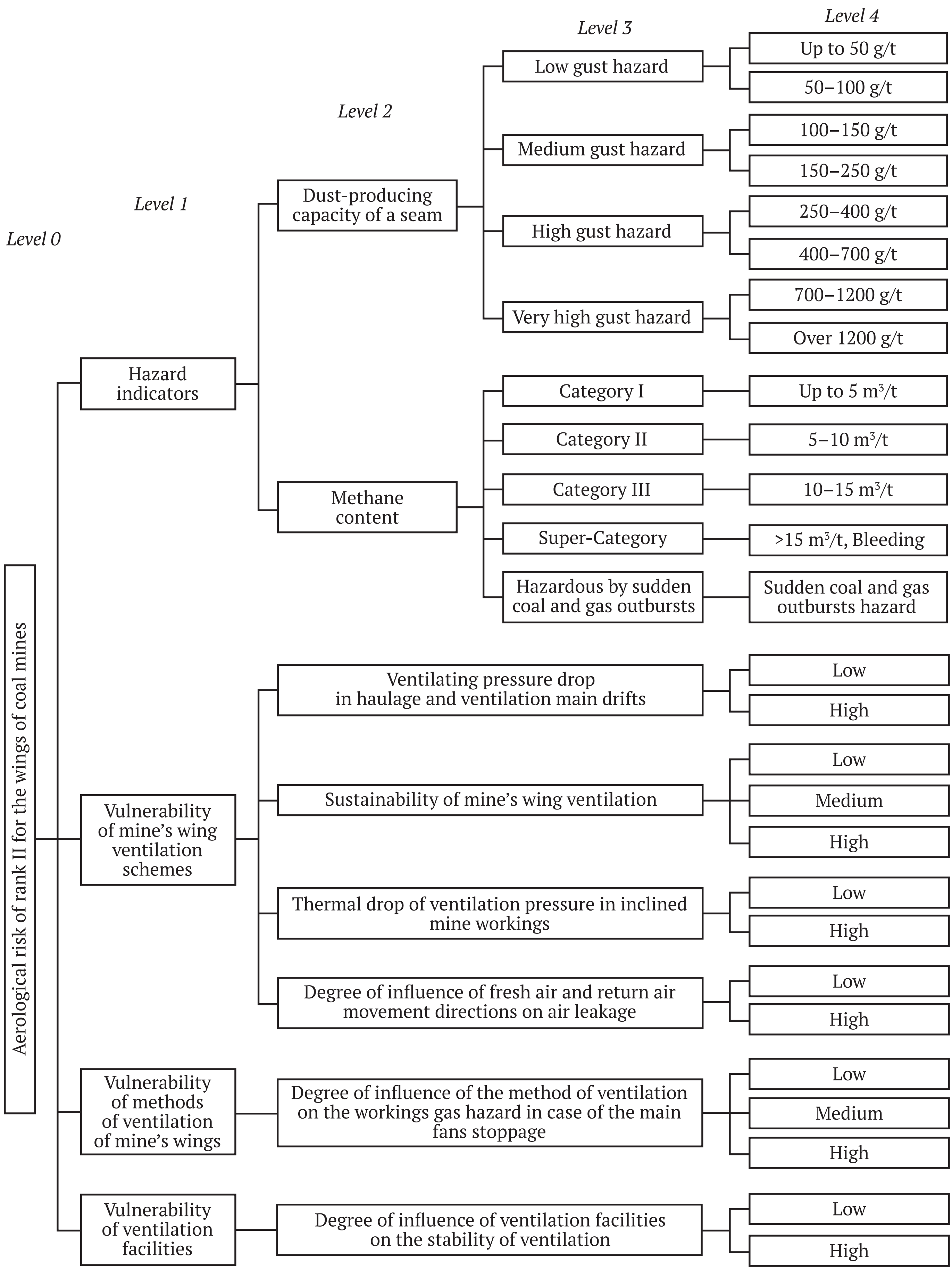

Fig. 2. Hierarchical structure of rank II aerological risks

Table 1

Rank I aerological risk values for super-category mines and mines hazardous by sudden coal and gas outbursts

Ventilation scheme and method	Rank I aerological risk values		
	Sustainability category 1	Sustainability category 2	Sustainability category 3
Flank scheme, suction method	0.078–0.535 / 0.093–0.611	0.101–0.575 / 0.121–0.657	0.203–0.733 / 0.242–0.838
Flank scheme, combined method	0.083–0.545 / 0.098–0.623	0.105–0.595 / 0.125–0.68	0.224–0.756 / 0.267–0.864
Flank scheme, blow-in method	0.087–0.556 / 0.104–0.635	0.108–0.615 / 0.129–0.703	0.245–0.78 / 0.292–0.891
Combined scheme, suction method	0.088–0.571 / 0.105–0.653	0.109–0.647 / 0.129–0.739	0.237–0.786 / 0.282–0.898
Combined scheme, combined method	0.1–0.599 / 0.119–0.685	0.133–0.685 / 0.159–0.783	0.262–0.808 / 0.313–0.923
Combined scheme, blow-in method	0.111–0.627 / 0.133–0.717	0.159–0.724 / 0.189–0.827	0.288–0.83 / 0.344–0.948
Central duplex scheme, suction method	0.105–0.614 / 0.126–0.702	0.179–0.715 / 0.213–0.817	0.3–0.832 / 0.357–0.951
Central duplex scheme, combined method	0.129–0.635 / 0.154–0.726	0.198–0.74 / 0.236–0.846	0.312 – 0.853 / 0.372 – 0.975
Central duplex scheme, blow-in method	0.152–0.656 / 0.182–0.75	0.217–0.766 / 0.259–0.875	0.325 – 0.875 / 0.388 – 1.000

Note: The numerator shows risk values for super-category mines, and the denominator shows risk values for mines hazardous by sudden coal and gas outbursts.

Table 2

Rank II aerological risk values for super-category mines and mines hazardous by sudden coal and gas outbursts

Ventilation scheme and method	Rank II aerological risk values		
	Sustainability category 1	Sustainability category 2	Sustainability category 3
Flank scheme, suction method	0.078–0.429 / 0.093–0.49	0.127–0.543 / 0.151–0.621	0.244–0.659 / 0.291–0.753
Flank scheme, combined method	0.088–0.48 / 0.105–0.548	0.141–0.589 / 0.168–0.673	0.258–0.707 / 0.308–0.808
Flank scheme, blow-in method	0.098–0.531 / 0.117–0.607	0.155–0.635 / 0.185–0.725	0.273–0.755 / 0.326–0.863
Central duplex scheme, suction method	0.093–0.514 / 0.111–0.587	0.146–0.607 / 0.174–0.694	0.252–0.719 / 0.301–0.821
Central duplex scheme, combined method	0.108–0.586 / 0.128–0.670	0.167–0.678 / 0.199–0.775	0.278–0.797 / 0.332–0.911
Central duplex scheme, blow-in method	0.122–0.658 / 0.145–0.752	0.188–0.749 / 0.224–0.856	0.304–0.875 / 0.362–1.000

Note: The numerator shows risk values for super-category mines, and the denominator shows risk values for mines hazardous by sudden coal and gas outbursts.

Conclusion

The steady trend of complication of mining and geological factors of coal mining associated with increasing the mining depth and the temperature of rocks, as well as the simultaneous intensification of mining operations with the use of up-to-date high-performance equipment cause growth of dynamic manifestations of natural factors of mining, such as sudden coal and gas outbursts, rock bursts, rock collapses, leading to gas and dust explosions and fires. This imposes additional requirements on the formation and functioning of the architecture of coal mine aerological safety, namely, the need for integrity of risk assessment for both a mine and its facilities, and hence flexibility, responsiveness, and interconnectedness of the organizational-technical and technological solutions for reducing the level of aerological risks.

Such requirements of aerological safety are met by a hierarchical structure of aerological risks at coal mines, which allows determining, for each mine and its individual facilities, the area of superposition of hazards of coal mining and vulnerability of schemes and methods of ventilation and ventilation facilities and quantifying these areas in the form of aerological risks. The presented methodology enables forecasting and reducing aerological risks in course of designing, operation, liquidation and conservation of coal mines.

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MINING MACHINERY, TRANSPORT, AND MECHANICAL ENGINEERING

Review article

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A systematic approach to the peat machines and equipment classification development

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Abstract
The «National Security Strategy of the Russian Federation until 2030» prioritises the use of resource-saving and waste-free technologies for natural resource extraction and processing, import substitution of mining equipment in the Russian mining sector, and the introduction of digital technologies at all stages of resource extraction and processing in the mining industry to improve their safety. The aim of the article is to study the gradual development of peat machinery classification and the relevance of its improvement through integrated mechanization devices to create waste-free extraction and processing of peat deposits using full-cycle mobile complexes with the development of environmentally friendly and resource-saving technologies for peat production. The methodological basis of the research includes post-event analysis, peat machine design theory, and systems analysis. As a research result, new system factors influencing the development of the classification of currently available machinery and equipment for peat production, as well as classification variants combining the processes of extraction and processing of peat deposit resources are provided, which allow modeling the structure of full-cycle mobile complexes for extraction and processing of peat deposit resources without waste. In terms of practical application, the classification of peat machinery enables the development of a rational decision-making data system for optimizing the structure of the technological machinery and equipment fleet of peat extraction enterprises, taking into account the deteriorating conditions of peat resources and development technologies, the economic conditions of the industry and the current trends of digitalization in the extractive industry.

Keywords
peat engineering, peat machinery, classification, system approach, methodology, design improvement directions, operating conditions

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ГОРНЫЕ МАШИНЫ, ТРАНСПОРТ И МАШИНОСТРОЕНИЕ

Обзорная статья

Системный подход к развитию классификации торфяных машин и оборудования

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Аннотация
В «Стратегии национальной безопасности РФ до 2030 г.» приоритетными направлениями являются: использование ресурсосберегающих и безотходных технологий добычи и переработки природного сырья, импортозамещение горной техники в горнодобывающем секторе РФ, а также внедрение цифровых технологий на всех этапах добычи и переработки сырьевых ресурсов в горных отраслях для повышения их безопасности. Цель статьи заключается в исследовании поэтапного развития классификации торфяной техники и необходимости ее совершенствования в связи с созданием средств комплексной механизации процессов безотходной добычи и переработки ресурсов торфяных месторождений с применением мобильных комплексов полного цикла с разработкой экологически безопасных и ресурсосберегающих технологий торфяного производства. Методологической основой исследования являются: ретроспективный анализ, теория проектирования торфяных машин и системный анализ.

В качестве результата исследования приводятся новые системные факторы, влияющие на развитие классификации имеющихся в настоящее время машин и оборудования торфяного производства, а также ее варианты, объединяющие процессы добычи и переработки ресурсов торфяного месторождения, позволяющие моделировать структуру мобильных комплексов полного цикла безотходной добычи и переработки ресурсов торфяной залежи. С точки зрения практического применения классификация торфяных машин позволяет разработать информационную систему для принятия рационального решения по оптимизации структуры парка технологических машин и оборудования торфодобывающих предприятий с учетом ухудшающихся условий эксплуатации торфяного месторождения, современного развития технологий разработки торфяного месторождения, экономического состояния отрасли и современных тенденций цифровизации в добывающих производствах.

Ключевые слова
торфяное машиностроение, торфяная техника, классификация, системный подход, методология, направления совершенствования конструкции, условия эксплуатации

Для цитирования
Zyuzin B. F., Yakonovskaya T. B., Zhigulskaya A. I. A systematic approach to the peat machines and equipment classification development. *Mining Science and Technology* (*Russia*). 2022;7(4):320–329. https://doi.org/10.17073/2500-0632-2022-06-06

Introduction

During the peat industry development period in Russia until the 1990s, peat enterprises were distinguished by their large scale, peat deposits exploration areas, production volumes, human resources and a high degree of production processes mechanization. All the technical equipment of peat mines was made in Russia, and different types of peat machines were mass-produced every year. The range of peat equipment was quite representative, which required the creation of a special classification of peat machines and complexes [1–4]. Peat extraction machinery was subject to a separate production technical specifications and had its own system of designation. The designs of machines for peat extraction and processing were very diverse due to the large number of different methods and technologies of peat production.

Today's operating conditions in the peat extraction and processing industry dictate new demands on technological peat equipment and machinery. The designs of domestic peat machines and technological equipment complexes developed before the 1990s do not meet these requirements. This can be explained by the technical characteristics of the machines and the imbalance of the operating conditions, the insufficient level of automation, the imperfect design and the catastrophic decline in peat production [5, 6].

In the last 30 years the crisis came over the domestic peat machinery industry: the decrease in the volume of manufactured and sold products, the narrowing of the range of manufactured technological machinery and equipment and, as a result, the complete extinction of most peat machinery manufacturers or their adaptation another type of products with a stable demand (municipal, agricultural, forestry, construction, road, transport and other vehicles). A significant part of the peat machinery market is represented by expensive imported machines [7, 8].

During the Soviet period of development of peat science and technology the main centers were: the Moscow Peat Institute, the All-Russian Research Institute of Peat Industry (VNIITP), the Research Institute GIPROTORF. In 1958, the Moscow Peat Institute was transferred to Tver and became the basis for the Tver State Technical University. In 2010, VNIITP was dissolved, and since then the center for peat science and technology has become the Tver Peat School. Over the past 20 years, new scientific peat schools have emerged in Russia in St Petersburg, Yekaterinburg and Tomsk. Each of them has their own scientific perspective on many theoretical aspects of peat science and technology, from issues of geology and exploration of peatlands, development technology, classification of peat technology, to issues of economic, legal and social development of the industry. On numerous occasions, one can observe in articles on various peat topics that established scientific concepts are substituted, that definitions from other branches of knowledge are misused, that known phenomena are rediscovered, that scientists violate copyright, distorting the obtained data of primary scientific importance. Such substitutions are, in our view, unacceptable because they can cause scientific confusion and mislead. For example, a number of papers have appeared in the last 2–3 years in which the authors argue that there is no “single” classification of machinery and equipment for peat extraction and processing in the peat industry.

In implementing the classification of peat machinery, we believe it is important to explain how the development process of the scientific classification of peat machinery and equipment proceeded. Why this process has been repeated and how the classification of peat machines has logically evolved over time and what classification features have been relied upon by the various authors is the purpose of this article.

Methodology of scientific views theoretical development research on the subject of peat machinery classification

The authors use a retrospective, critical analysis of the known classifications of peat extraction machinery to examine the theoretical development of scientific views on the classification of peat extraction machinery. The development of the design of machines that exploit peat deposits and extract and process peat resources is closely related to the methods and technologies used in the peat industry. The first peat machine was developed by I.F. Hoffman in 1843 [2, 4, 6], and since then there has been a rapid development of peat machines of various designs, which allow mechanizing partial operations of the technological cycle of peat extraction. It should be noted that the engineers and designers of peat machines often gave names to their machines, using their surnames (e.g. Sarmatov's shredding drum, Rogov's press, etc.). In 1931, at the Moscow Peat Institute, the scientific discipline "Peat Machinery» was established, headed by Professor M.I. Sarmatov, and the scientific course "Hydropeat process machines" was headed by Professor I.N. Glybovsky. In the 1950s, the Moscow Peat Institute was transferred to Kalinin (now Tver), and the Tver State Technical University became the center of peat science, where leading figures in peat science have worked to this day. Following scientists have specialized and specialize up to the present day in the peat engineering subject: M.V. Murashov, F.A. Opeiko, S.G. Solopov, L.N. Samsonov, L.O. Gortsakalyan, V.I. Tsvetkov, B.F. Zyuzin, V.F. Sinitsyn and others. Up to 1948, the term "classification» of peat machinery was not used, and only Professor S.G. Solopov in his book introduced this term for the first time, making an attempt to classify peat machinery. His classification is introduced in writing and presents peat machines in groups based on the principle of the extraction method and the course of the technological cycle of peat extraction. The emphasis is given to peat deposit development hydraulic method and dredging-and-hoisting machinery [6]. However, as the milling method of peat extraction became particularly popular in the late 1950s due to its high technical and economic indicators, the need arose to study the work of the main extraction machine – the milling drum (milling machine). Therefore, M.V. Murashov was the first to make a written classification of milling machines in his dissertation in 1964, based on the following principles: mining method; relationship to the wood inclusions milled in the deposit; technological purpose; design of the milling bit; design of the milling mold and mining elements. In addition, since the milling bit is the extraction machine directly involved in the extraction of peat from the peat deposit, special attention was paid to the interaction with the peat and wood inclusions. Thus, in the work of F.A. Opeiko [9] there is a tabular classification of crawlers and peat cutting equipment according to the number of degrees of freedom of the cutting elements and the type of operation performed. It is noteworthy that in the classification of F.A. Opeiko the development of the design of the peat machines is closely connected with the increase of the degrees of freedom of the excavation equipment. He also points out that the classification of peat machines based on the operations of the peat extraction cycle can not be uniform and clear enough, because one machine can perform several operations and have multifunctionality, or part of the operations, but one or another machine system can be out of order. It is worth mentioning that it was F.A. Opeiko who put forward the idea that with the increasing technical level of peat machines and the complexity of calculations in their design, it is necessary to take into account not only the experimental data of their work, but also "*...the possibilities of modern simulation and digital computing devices*". And exactly with the above-mentioned statement of F.A. Opeiko in 1968 began the automation process and the use of digital devices in the design and control of peat machines, the centralization of the design process and control in the management of peat companies. This direction founding fathers can be rightly considered the representatives of the Tver peat school [10]: N.M. Karavaeva, A.I. Burakov, V.I. Kuznetsov, A.N. Volkov, G.A. Dmitriev, B.V. Palyukh. The development of peat machinery is complicated by the complications of extraction, geological and climatic conditions, and the development of technologies for peat extraction, especially the mechanization of peat production, integrated mechanization, automation, and digitalization (Fig. 1).

The next milestone in the development of peat machine classification is considered to be the work of Professor S.G. Solopov in 1972 [11]. This is the second modification of the classification he developed in 1948, which differs in that the terms "complex" and "complex unit" appear in it, which no one has ever used in peat engineering. Basically, Professor S.G. Solopov has developed three peat machinery classifications, but his work of 1981 [12] lacks a complex unit for drying peat on sieves in a stack. Peat machines in his classifications are grouped by the type of dry peat (lumpy and milled crumbly peat) and by the technological process operations of the peat deposit development.

Considering the development of the economic use of peat in the Soviet period and today, almost every year scientists develop new types of peat products that require a different degree of processing of the original peat raw materials. Therefore, the need to classify peat processing equipment arose, and in 1990 Professor O.S. Gorfin was the first to develop a classification of equipment for peat processing plants [13]. By the beginning of 1990, most of the peat deposits in the regions of the European part of Russia had been mined, peat extraction and geological conditions were deteriorating, leading to a decline in the quality of the peatlands affected by the development. One of the most important quality indicators of peat deposits, in addition to the degree of decomposition, is the degree of stumpage. The higher the percentage of buried wood in the deposit, the lower the productivity and quality of peat extraction (stratification and surface extraction or deep extraction). In this context, B.F. Zyuzin in 1989 in his work [14] gives a detailed classification of peat mills, considering them as the main driving element of peat extraction machines. Changing economic conditions in Russia and the sharp decline in peat mining have led to the need to develop new technologies for peat extraction and processing. And for this reason, in 1999, Professors L.N. Samsonov and V.F. Sinitsyn improved the classification of peat machines proposed in 1981 by Professor S.G. Solopov. Also known is the classification of Professor V.D. Kopenkin from 2002 [15], in which he combines the classification of mining machines and the classification of the main structural elements of peat machines and complexes. At the same time, he proposes to consider peat machinery as a subclass of mining machinery and equipment and uses the term "geomachinery". The peculiarity of the classification of V.D. Kopenkin is that on the basis of the study of the classification of mining machinery, he proposes to use some of them (heavy crawler dozers, excavators) for the development of peat deposits. He refers to the lack of available Russian peat machines and the use of quarry machines abroad [16–19]. Therefore, it is necessary to present the course of the history of development of the classification of peat machinery in a graph prepared by the authors according to the method of V.D. Kopenkin to study the flow of scientific information on the subject of classification of peat machinery and equipment (Fig. 2).

As can be seen from Fig. 2, the development of views on the peat machines and equipment classification has a long history and three stages of scientific development (segments: A, B, C), which are closely connected with the changing conditions of peat enterprises industrial and economic activity, namely: economic, mining and geological and technological, related to the improvement of peat deposits development methods and technologies (geotechnology). And each subsequent classification was an improved

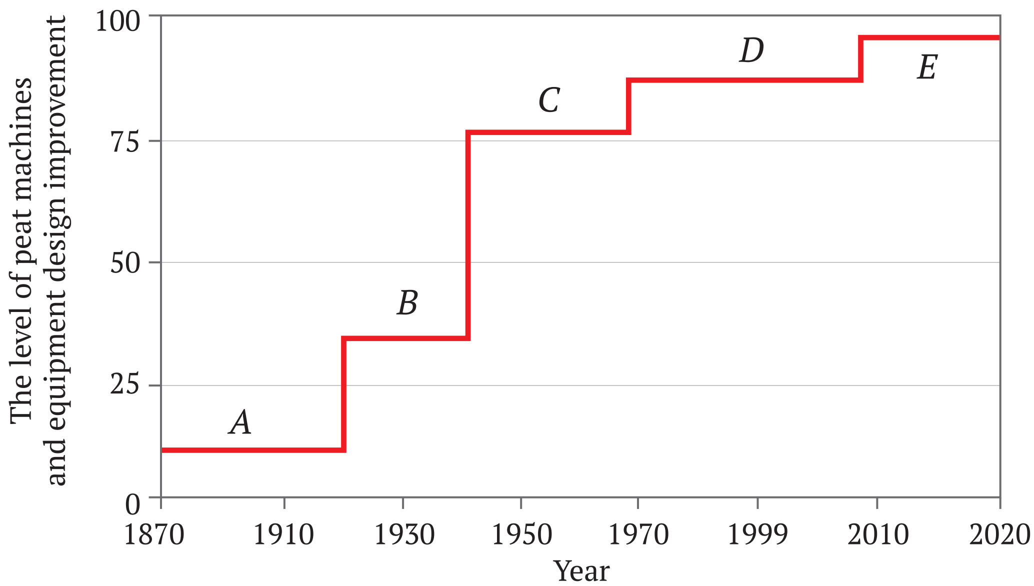

Fig. 1. Levels of peat machinery designs improvement (compiled by the article authors): *A* – partial mechanization; *B* – mechanization; *C* – comprehensive mechanization; *D* – partial automation; *E* – automation and partial digitalization

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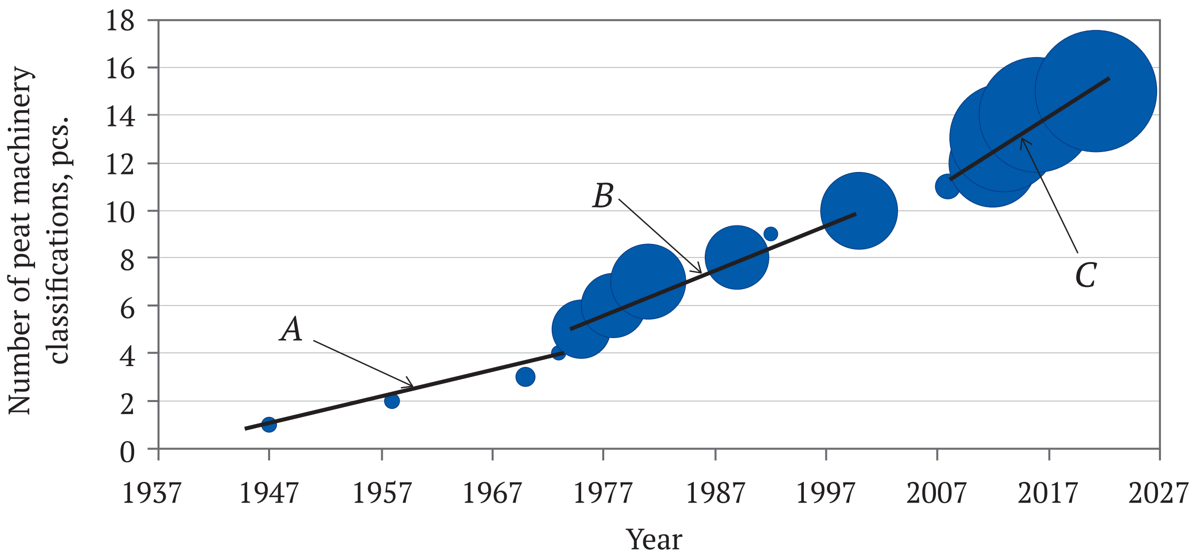

Fig. 2. Peat machine classifications development (compiled by the article authors)

modification of the previous one (marked by large circles). Some of its structural elements (indicated by small circles) depend on the development of the working tools and the chassis of the peat machines and represent separate scientific fields. The aim of these directions manifests itself in a thorough and detailed study of the interaction processes of the working elements of peat machines with the peat deposit, which has various geological, structural, physical-mechanical and hydrodynamic characteristics. The last (third) phase of the development of academic interest in the classification of peat machinery began in 2012 and is characterized by the introduction of selective geotechnologies for peat extraction using hybrid, universal, mobile and autonomous complexes of peat machinery and equipment determined by the trend of digital transformation of technological processes in the extractive industry [20–22].

Using a systematic approach to the development of a peat machinery comprehensive classification

Classification is a general scientific method of knowledge systematization aimed at organizing a certain combination of studied objects from different areas of reality, knowledge and activity into a system of peer groups (classes) in which these objects are distributed on the basis of their similarity in certain essential properties. The Great Soviet Encyclopedia defines classification as “a system of subordinate concepts (classes of objects) of any field of knowledge or human activity, often presented in the form of schemes (tables), which serves as a means of establishing connections between these concepts or classes of objects, as well as for precise orientation in a variety of concepts or corresponding objects”. The classification main tasks consist in fixing relations and patterns between objects that have the same properties, as well as storing and retrieving data. In this regard, any classification can be seen as a database prototype. From this point of view, classification enables the development of science and machines, starting with the accumulation of theoretical knowledge and ending with their systematization. Classification, based on sound scientific knowledge, makes it possible to identify the actual state of science, machinery or its structural elements and to evaluate their development appropriately [23–25].

To develop peat machinery classifications, the authors used the system approach principles and methods. The system approach makes it possible to reveal the object integrity by defining various relations, which form a comprehensive and integral view of the object under study. From the system approach point of view, classification is a complex ordered system of elements, united by structural links to achieve a certain objective (Fig. 3).

System analysis allows affirming a strong connection between peat production technological machines, peatland exploration conditions and peat extraction and processing technologies [26, 27]. The change and improvement of peat extraction technologies leads to the need to develop new machines and improve their design. Thus, the factors affecting the development of peat resources extraction and processing technologies have a direct impact on the design of peat machinery and the completion of technological complexes [28, 29].

Research results discussion

The analysis of Fig. 3 shows that the classification of peat machines is constantly improving due to the influence of objective system factors. These factors include: the development of peat geotechnologies, the improvement of peat machinery design to improve its performance characteristics, the cheapening and import substitution, the development of modern mining machinery, the deterioration of mining, geological and climatic conditions of peatlands, and economic, legal and organizational conditions. Taking into account the listed factors, four modifications of the peat machine classification have been proposed by article authors since 2012, each of which is the logical continuation of the previous one and is presented in the published works [2, 4].

The classification of peat machines in the 2012 article [4] was developed based on the type of peat deposits extracted. This classification for the first time distinguishes “peat-wood raw material” as a separate type of raw material, and thus the structure of peat deposit raw material includes: peat; woody raw materials obtained during the consolidation of woody vegetation in the technological process of preparing the peat deposit for development; peaty and woody raw materials obtained in the technological process of deep (continuous) peat extraction together with woody vegetation growing on the peat surface and buried wood in the thickness of the peat mass.

In view of the similarity of the technological process of peat deposit preparation for development with the similar processes in other nature exploitation branches (for example, mining, logging, etc.) and the absence of mass production of peat machinery in Russia the authors include in the classification the machines of the forestry, mining, agricultural, construction and road complexes. This allows to derive a new definition of peat complexes – “Mixed complexes”.

The classification of peat machines in the work [4] differs, as new features are taken into account – “peatland development conditions» and “type of production organization”, which allow to filter out new machine complexes: “mobile peat machines for on-site peat extraction and processing» and “energy self-sufficient peat complex”. The 2020 classification shown in Fig. 4, complexes have been added to distinguish equipment for the safe storage of peat, wood, peat-tree raw materials; mobile processing, loading, transportation and receipt of peat and peat-tree resources.

In the context of the outlined global tendency of the transition of mining industries to the ideology of Mining 4.0, complication of economic-political and mining-geological conditions for the development of peat deposits and the need to optimize the range of peat products, as well as the use of selective geotechnologies, the authors introduce the principles of peat classification into a new complex classification: “complexity of technology for the development of peat deposits”, “degree of mechanization, automation and digitalization of peat technology processes”. Given principles made it possible to distinguish “Hybrid and selective geotechnologies” and the corresponding “Peat machines hybrid complexes”, which imply automated, autonomous, robotic and digital control. Such “Hybrid complexes” will allow peat production to enter the digital transformation era of extraction and processing technological processes of peat deposit raw materials [5].

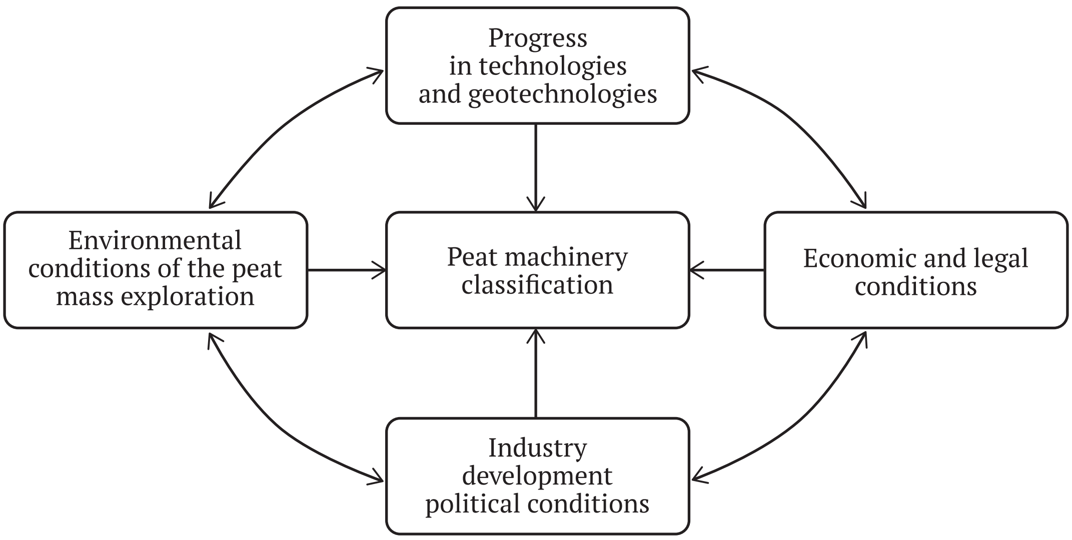

Fig. 3. Systemic factors influencing the peat classification development (compiled by the article authors)

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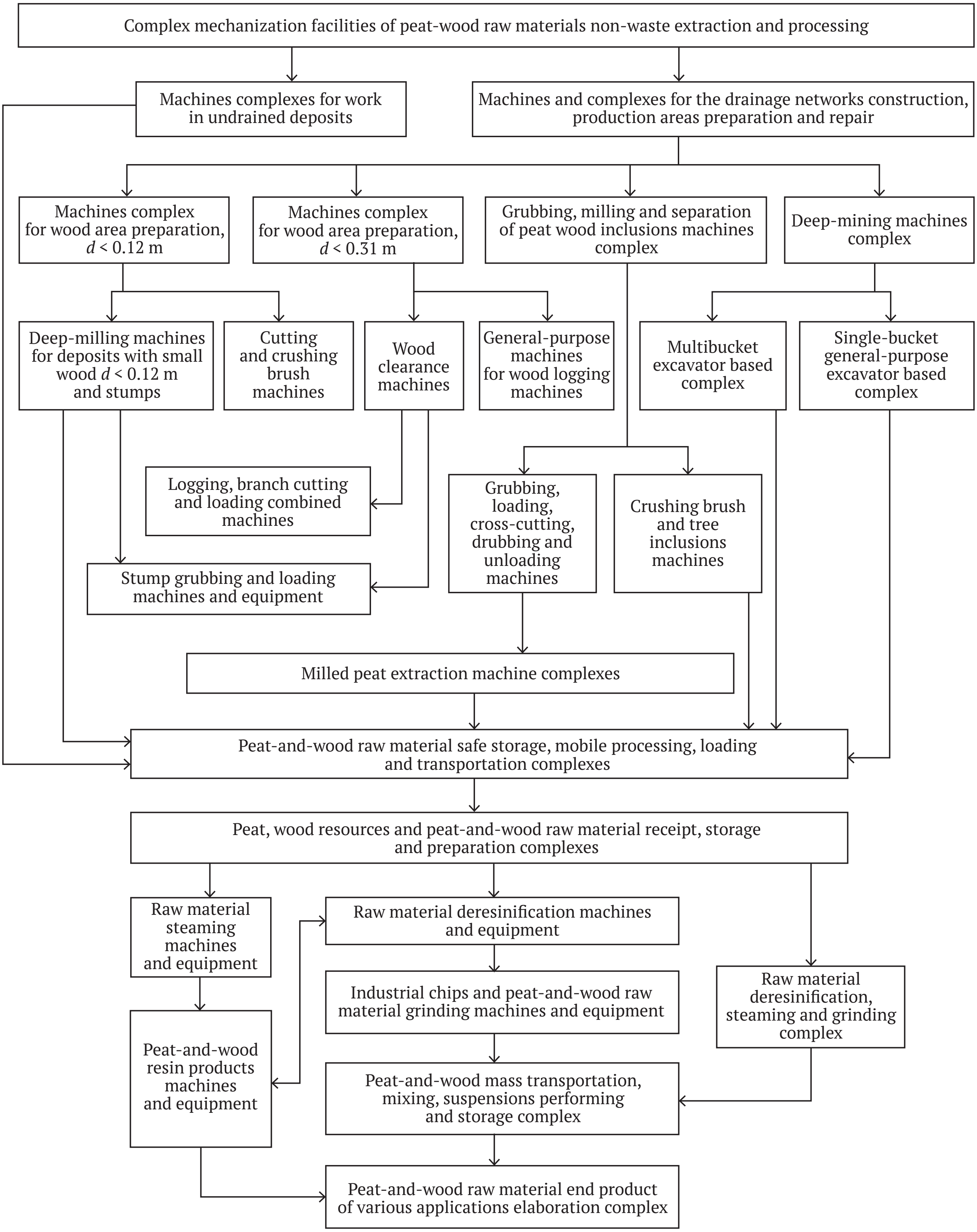

Fig. 4. “2020 Peat Machinery Classification” segment for the peat-and-wood raw materials production (compiled by the authors)

Conclusion

As a result of the research, the authors made the following conclusions:

1. The classifications of all peat machines have been developed according to the main law of connection between the technological equipment and methods of exploitation of peat deposits and the production cycles of peat extraction and processing.

2. In the classification proposed by the authors, due to the development of scientific views on the problem of selective peat deposits and the deterioration of the conditions of development of peat deposits, the principle of "Hybrid complexes» was introduced.

3. The authors point to a new type of peat raw material – the "peat-and-wood raw material" – which consists of buried wood, stumps, that were considered waste in the peat development of traditional technologies, cleared and sent to the landfill and then processed into low-grade firewood.

4. The obtained peat-and-wood raw material requires a new type of equipment. Therefore, the authors introduce the principle "Type of obtained raw materials" into the classification.

5. Considering the mining digitalization development, the authors introduce the principle "Peat technological processes mechanization, automation and digitalization levels" for the peat machines classification.

6. Since in Russia the peat machine building market is represented mainly by foreign machinery, and domestic peat machines are custom-built, the authors suggest using machines from other nature-operating branches with similar working principle (mining, logging, agriculture sector et al). In view of this, a new term may appear in the classification of peat machinery, characterizing the improvement directions of geotechnologies for the development of peat deposits – "mixed (hybrid) complexes and technologies".

7. There are two vectors of the peat machinery classification development: 1. according to the technological process of the peat deposit development, performed operations type and received raw material type (peat crumbs, grains, lumps, hydromass, peat-and-wood raw material, peat water, off-grade wood, peat dust, wet peat (dry peat)); 2. according to the structural elements type (classification: chassis, working tools, engine type, drive type, control type, et al.).

8. From a system approach perspective, the authors believe that the peat machinery classification should not be constant. It should dynamically develop under the influence of the factors acting on it, allowing to predict and foresee the possible directions of the peat machinery complexes development.

9. Since the peat machinery classification is systematic, was developed and evolves under the influence of the system factors affecting it (for instance, various technological sanctions, the Russian state industries digital transformation program, "neutral carbon footprint" technology, "green technologies"), then, considering Mining 4.0, further design improvement of all types of peat complexes will become more complicated due to the introduction of the artificial intelligence and IT technologies elements in the peat machines design.

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Value chain stress resilience and behavioral strategies of companies in Russian coal industry

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Abstract

Under the current conditions, the Russian coal industry is under unprecedented external pressure: it is both the imposed sanctions and the need to meet strict environmental requirements that inevitably lead to the closure of part of the enterprises, the collapse of value chains (VCs) in the coal and related industries. As a result, a complex restructuring of the industry is required. To carry it out successfully, a reliable criterion is needed to assess the prospects for the long-term development of both individual companies and VCs as a whole. From the authors' point of view, the degree of stress resilience of VCs is the criterion needed.

The article deals with the evaluation of the long-term development prospects of the coal industry based on the established stress resilience of VCs and the related strategies of coal companies' behavior. The authors proposed an algorithm for assessing the stress resilience of VCs in the coal industry: a description of the aspects and typology of VCs in the Russian coal industry; an assessment of their current stress resilience; a description of the survival strategy of the companies included in the VCs; an assessment of the prospects for sustaining VCs under sanctions. Subsequently, this article presents theresults of the stress resilience assessment of 169 coal companies operating in 110 different VCs between 2010 and 2021.

The authors created a typology of VCs in the coal industry, which makes it possible to identify three basic types of VCs in the domestic coal industry: two integrated – the captive market and the hierarchical market – and one non-integrated market. Analysis of companies operating from 2010 to 2021 showed that 90 out of 169 businesses (53%) operated as integrated companies (hierarchical and captive VCs), the remaining 79 were classified as market ones.

For each type we measured overall stress resilience (β_{rescom}), indicating the VC degree of recovery from shocks; robustness (β_{res}), the VC ability to withstand (swallow) shocks; adaptability (β_{rec}), the VC flexibility CDS and the ability to recover quickly after a shock. The analysis conducted by the authors showed that the stress resilience of key segments of the coal industry is low and tends to decrease and will only decrease in the long run. The research also found that systemically important companies are in the most difficult situation. They belong to the hierarchical VCs, especially the energyand coal companies, which are mainly focused on foreign markets. Their cooperative survival strategy does not even maintain the current level of stress resilience. Market and relational VCs are in a more favorable position. As a result, the authors conclude that part of the coal companies will inevitably close and for the other part a profound restructuring will be necessary, while the current survival strategies of the companies will not allow to solve this problem by themselves and an active participation of the state will be necessary.

Keywords

coal industry, stress resilience, value chains (VCs), typical coal industry VCs, company behavioral strategies

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ОПЫТ РЕАЛИЗАЦИИ ПРОЕКТОВ В ГОРНОПРОМЫШЛЕННОМ СЕКТОРЕ ЭКОНОМИКИ

Научная статья

Стрессоустойчивость цепочек добавленной стоимости и стратегии поведения компаний в российской угольной отрасли

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Аннотация

В современных условиях российская угольная отрасль столкнулась с небывалым внешним давлением: это и введенные санкции, и необходимость соответствовать жёстким экологическим требованиям, что неизбежно ведет к закрытию части предприятий, разрыву цепочек добавленной стоимости (ЦДС), сложившихся в угольной и смежных отраслях. Требуется сложная реструктуризация отрасли, для успешной реализации которой необходим надежный критерий, позволяющий оценивать перспективы долгосрочного развития как отдельных предприятий, так и ЦДС в целом. По мнению авторов, таким критерием является уровень стрессоустойчивости ЦДС.

Статья посвящена оценке долгосрочных перспектив развития угольной отрасли на основе стрессоустойчивости сложившихся в ней ЦДС и связанных с ними стратегий поведения угольных компаний. Авторы предложили алгоритм оценки стрессоустойчивости угольных ЦДС: описание особенностей и типологизация ЦДС, сложившихся в российской угольной отрасли; оценка их текущей стрессоустойчивости; описание стратегии выживания компаний, входящих в состав ЦДС; оценка перспектив сохранения ЦДС в условиях санкций. Соответственно, в статье приведены результаты оценки стрессоустойчивости 169 угольных компаний, действующих в рамках 110 отдельных ЦДС в период с 2010 по 2021 г.

Авторами произведена типологизация угольных ЦДС, что позволило выделить три базовых типа ЦДС в отечественной угольной отрасли: два интегрированных – посреднические и иерархические рыночные, и не интегрированный – рыночный. Анализ компаний, действовавших в период с 2010 по 2021 г., показал, что 90 из 169 предприятий (53 %) действовало в составе интегрированных компаний (иерархические и посреднические ЦДС), остальные 79 были отнесены к рыночным.

Для каждого из типов ЦДС были измерены общая стрессоустойчивость (β_{rescom}), которая показывает степень восстановления ЦДС после окончания шока; робастность (β_{res}) – способность ЦДС противостоять (поглощать) шокам; адаптивность (β_{rec}) – гибкость ЦДС и способность быстро восстанавливаться после шока. Проведенный авторами анализ показал, что уровень стрессоустойчивости ключевых сегментов угольной отрасли невысок, имеет тенденцию к падению и в перспективе будет только снижаться. В результате исследования выявлено, что в наиболее тяжелом положении находятся системообразующие компании, входящие в состав иерархических ЦДС, особенно энергоугольные, которые ориентированы преимущественно на внешние рынки, кооперативная стратегия выживания которых не обеспечивает поддержания даже текущей стрессоустойчивости. В более благоприятном положении находятся рыночные и отношенческие ЦДС. В итоге авторы делают вывод, что часть угольных компаний неизбежно закроется, а для другой части потребуется глубокая реструктуризация, при этом текущие стратегии выживания, выбранные компаниями, не позволят решить эту проблему самостоятельно и понадобится активное вмешательство со стороны государства.

Ключевые слова

угольная отрасль, стрессоустойчивость, цепочки добавленной стоимости (ЦДС), типичные ЦДС угольной отрасли, стратегии поведения компаний

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Introduction

The Russian coal industry has faced the need to adapt to increasing sanctions pressure and stringent environmental requirements. Under the fifth package of sanctions alone, the European Union banned the coal and other solid fossil fuels import and transit from Russia. This affected 25 % of all Russian coal exports, amounting to about €8 billion, and significantly limited the demand for Russian coal, whose production is almost 50 % foreign-oriented [1].

Sanctions lead to the collapse of established VCs in the coal and related industries, which in turn contributes to the formation of additional risks that are impossible to assess and reduce without analyzing the stress resilience of VCs.

In addition, the VCs analysis is an important tool for studying the formation and development processes of promising industries. In contrast to traditional microeconomic and macroeconomic analyzes of markets, VC analysis has a strong dynamic character. It makes it possible to define possible strategies for the industry and to assess the long-term sustainability of different groups of coal industry companies, identifying their full range of potentially available development paths, including those based on "clean" coal technologies and aimed at creating competitive products. Therefore, VC analysis, which focuses on finding promising transformation paths based on identifying the spectrum of available technologies, can become an effective tool for formulating strategies for the development of coal mining regions.

1. VCs stress resilience modern approaches review

The concept VC and stress resilience as a tool for evaluating the prospects for their long-term development are quite new. For this reason, it is necessary to clarify the content of the concepts before assessing the stress resilience of domestic coal mining companies .

Until the 90s of the XX century, the company was the basic unit of industrial analysis. However, the distributed (network) model of active formation of industrial technology, based on the division of branches of work, led to the strengthening of technological integration and became the basis for the formation of stable inter-firm cooperation – value chains (VCs). VCs began to play a leading role in ensuring the competitiveness of both individual companies and industries as a whole, which led to the VC concept creation [2–4]. The most famous VC definition was given by Timothy Sturgeon: "a value chain is a complete set of actions that is necessary to promote a product from its conception to the end consumer through all stages of production, including development and design, raw materials and provisional components supply, production itself, marketing and distribution, as well as providing after-sales service" [5]. Modern VCs are extremely diverse, they use various advantages of technological cooperation, companies organizational cooperation, therefore, within the VC concept there are many approach, using not only different terms to define VC, but also different notions [6, 7].

Modern literature introduces several approaches that use close notions to designate VC and describe its different aspects. Thus, M. Porter, 1985; Gereffi, 1994 [8, 9] use the concept of "commodity chains" and understand them as product creation stages within separate companies, represented by key and substantive activities. In technical studies that analyze alternative uses of intermediate products and/or industrial recycling of a resource/waste, VCs are called process chains. Research that examines ways to reduce the cost of end products by redesigning production processes, intra- and inter-firm logistics solutions refers to VCs as supply chains [10]. This approach is close to the added value chains and production networks researches, describing, respectively, the sequence of adding value stages to a product, starting from mineral resources extraction to the finished product, and the VCs organizational structures: the main types of actors, the mechanisms of chain management, and the nature of interaction between firms in the supply chain and with the external environment, especially markets, supporting infrastructure, and institutions [11–13]. The VC scale and structure can be traced in the concepts of "global, local or domestic VCs" (global value chain (GVC), domestic value chain (DVC) or local value chain (LVC) [14–17].

Despite the differences in the terms determined by the analysis and the scope of the research objectives, all the above approaches distinguish in the basic model of VC three VC key components that are interconnected:

– supply chain, which describes the key blocks in terms of distributed production – the key production and service stages in creating the final product or service;

– VC organizational model, which identifies the key chain organizational links, describes each and shows connections between them, characterizes the decision-making center and operation modes;

– value chain, which characterizes VCs in terms of how the value is formed and distributed between the VC main links.

These three blocks are closely related and mutually limit each other. The leading role belongs to supply chains because they "are complex systems consisting of organizational, informational, financial, technological, process, product and energy structures" and determine the basic options for the VCs construction. The organizational model and value chain narrow the range of options available, defining commercially successful options [18].

The dramatic increase in economic turbulence has led to another industry research innovation. The current competitiveness studying began to be expelled by the need to study the companies and industries ability to withstand internal and external negative factors (shocks). This led to the emergence of researches dedicated to the VCs stress resilience [18–20]. Stress resilience differs from classical competitiveness theory in that it allows describing the possibility of VCs sustainable functioning and modernization under conditions of continuously changing external environment. The OECD report defines it as "the ability of a system to flexibly recombine its elements and resources to achieve a dynamic equilibrium at either the previous or a new level of development in response to sudden external or internal perturbations" [21].

Before proceeding to the evaluation of the stress resilience of the Russian coal industry VCs, it is necessary to address another problem. The coal industry, like the majority of extractive industries, is falling "behind" in the VCs formation. This is due to the fact that, unlike manufacturing industries, extractive industries have predominantly developed within closed (enclave-like) vertically integrated enterprises based on additive supply chains, which are a series of successive stages of demand that cannot be carried out in parallel – all products of the previous stage are supplied to the subsequent stages as stock. The main competitiveness source of coal companies was the scale of operations expansion based on access to unique natural resources and location. For this reason it did not make good sense to build VCs and distinguish the main links affecting the risk level and competitiveness special sources. The intensification of mining processes under the influence of the depletion of readily available resources and the globalization of the economy resulted in the VC end-to-end productivity from coal mining to the market becoming a real source of added value, leading to an increase in the intensity of production, the role of ancillary industries and services, the complication of the structure of coal companies and the creation of sustainable links with companies from related industries. Accordingly, this opened up opportunities for a substantive study of the VCs aspects and their stress resilience factors in the extractive industries, including the coal one [22–26].

The authors of the article use the concept of "value chain" to denote the basic model of VCs and the concept of "supply chain" to denote the technological chain, and all these concepts are based on the concept of VC stress resilience (Aldrighetti R. et al, 2021) as "the ability of the enterprise to withstand, adapt, and recover from failures in order to meet customer demand, ensure target productivity, and sustain operations in a vulnerable environment" [18]. In relation to the coal industry, stress resilience means the ability of individual coal companies and groups of interconnected companies to anticipate and respond to change in order to survive in the short term (cost reduction, formation of new technological chains, etc.) and to seek and implement new development opportunities in the long term (formation of new supply chains in the implementation of the Industry 4.0 concept and response to external challenges: decarbonization, sanctions policy, energy transition, etc.).

2. Data and research methodology

Within the article, the authors proposed the following algorithm for the stress resilience of VCs in the coal industry: description of the aspects and typology of VCs in the Russian coal industry; assessment of their current stress resilience; description of the survival strategies of VCs; assessment of the prospects for the preservation of VCs under sanctions.

To identify VCs typical of the Russian coal industry, the authors analyzed official data from the Federal Service for State Statistics of the Russian Federation, the Central Control Administration of the Fuel and Energy Complex (CCA FEC), Rosinformugol JSC (AO), and the electronic accounting and inventory system (SBIS) for 169 companies operating in the period from 2010 to 2021. The time period was defined by the boundaries of two crises waves in 2010–2017 and 2018–2021.

The Gereffi, 2005 methodology was used to classify coal industry VCs, where five VC types were singled out: market, modular, relational, captive and hierarchical [27]. To clarify the nature of the relationships between the companies and with companies in related industries, interviews were conducted with five experts from among the top managers in the coal industry. Thus, based on criteria such as the structure of the supply chain and the organizational model, we were able to identify the basic types common to the domestic coal industry, highlight their aspects, and show the survival strategies of the companies that belong to them. As a result, of the five VC basic types common to the coal industry, three VC types were identified: market, captive and hierarchy.

To assess the potential success as well as the ability to maintain the chosen strategy in the future under sanctions and a possible embargo on coal supplies, the stress resilience of both VCs and VCs companies was examined for the periods from 2010 to 2017 and from 2018 to 2021. For this purpose, all 169 companies were divided into three large VCs groups according to their proximity to basic model one or another type. Due to the fact that hierarchical VCs exhibit different survival strategies depending on their specialization, the hierarchical VC type was further divided into three subtypes. Subsequently, the stress resilience of VCs and selected VCs companies was evaluated based on the methodology of R. Martin, which proposes to evaluate the stress resilience of different systems based on the stress resilience coefficients (β) [28]. According to this methodology, the selected type and subtype were measured in each VC: general stress resilience (general stress resilience coefficient – β_{rescom}), which shows the VC recovery degree after a shock; robustness (resilience coefficient – β_{res}), which shows the VC ability to resist (absorb shocks); adaptability (recovery coefficient – β_{rec}), reflecting VC flexibility and ability to recover quickly after a shock.

These coefficients were calculated for two periods: the first period – from 2010 to 2017, the second one – from 2018 to 2021. The periods were determined basing on the analysis of the production volumes dynamics in the domestic coal industry. The beginning of the period was determined on the basis of the year in which the growth rate of production was the highest. The crisis year was determined based on the year with the lowest growth rate or the highest rate of decline in coal production. The final year is the year in which the growth rate of production has returned to the original value or the highest growth was recorded during the recovery period.

All three stress resilience coefficients were calculated using the same formula:

$$\beta = \frac{\left[\dfrac{Q_t^c - Q_{t-1}^c}{Q_{t-1}^c} - \dfrac{Q_t^i - Q_{t-1}^i}{Q_{t-1}^i}\right]}{\left|\left(Q_t^i - Q_{t-1}^i\right)/Q_{t-1}^i\right|},$$

where Q_t^c is the coal production volume within the VC group, in thous. tons; Q_t^i is the coal production volume of within the industry as a whole, in thous. tons; $(t-1)$ for β_{rescom} and β_{res} are the initial years of the pre-recession shock (2010 and 2018); for β_{rec}, the years of the largest production decline (2013 and 2019); t – for β_{rescom} and β_{rec}, the years of the recession recovery (2017 and 2021); for β_{res}, the peak production decline years within the industry (2013 and 2019).

The stress resilience coefficients calculations data for each VC type and subtype is introduced in the next section.

3. Domestic coal industry VCs aspects and their stress resilience level

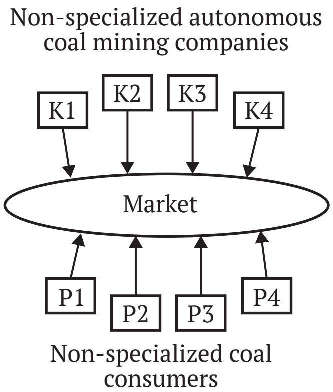
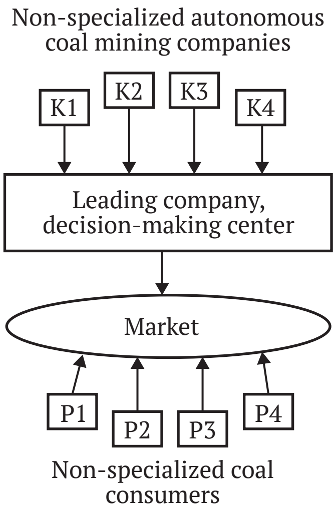
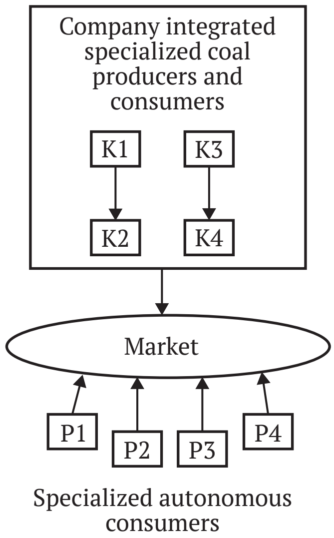
The coal industry resource nature and industrial engineering aspects generate the coal industry VCs specific character in all three components. As noted by many authors [22–27], the coal industry primary costs constitute a significant part of the final product value and vary greatly depending on the coal assets specific characteristics and company location, so that not so much improvement as production losses determine the final value of coal value added. Due to the dependence on mining and geological conditions, as well as the qualitative and quantitative composition of the resources of the coal chain, most of the value added is in the production stage, which includes the preparatory stages, mining and processing [24]. Access to natural resources and the availability of transportation and logistics infrastructure largely determine the location of coal mining companies. For this reason, the coal industry has not been able to become distributed. Distributed production is an industrial engineering model focused on a detail-based labor division between highly specialized VCs participants working for each other. The creation process of the final product is distributed among a number of autonomous company-suppliers from different countries and regions, united under the leadership of one or more leading companies in the common project network VC, performing their narrow, highly specialized task in the project (VC link), consistently adding value to the final product at each stage of the production cycle [19]. The coal industry supply chain is still shortened and has a fairly lean additive structure [20, 22].

The authors dealing with coal industry VCs management and organizational structures refer them to vertically down controllable productions [20, 22, 25, 26]. The majority of VCs are referred to global closed (enclave) vertically integrated VCs of hierarchical type (Glencore, BHB Biliton, Anglo American, Siberian Coal Energy Company (SUEK), Kuzbassrazrezugol, etc.) [25, 26]. Experts point out the volatility of the coal industry, especially because of the strong negative impact of price and demand fluctuations in global markets [25, 26–31] and weak innovation susceptibility [26, 31].

An analysis of the companies operating between 2010 and 2021 showed that 90 of the 169 (53 %) operated as integrated companies (hierarchical and captive VCs). They were united in 13 VCs, which composition was relatively constant. 79 enterprises were formally autonomous companies (market VCs). Among the 43 companies in the hierarchical VCs, the following specialization was found: 6 companies specialized in energy-coal, 6 companies specialized in metallurgy and coke-chemistry, and 1 company specialized in cement. Specialization was determined by the major firm consumer. 47 companies were part of 18 intermediary-type VCs –non-specialized conglomerates with no explicit specialization. Autonomous companies had no specialization and were part of market-type VCs. Brief descriptions, typical VCs schemes of the Russian coal industry, and examples are shown in Table 1.

Table 1

Typical Russian coal industry VCs (*N* = 110)

VC types/sample number	Market VCs	Captuve VCs	Hierarchical VCs
VCs sample number	79	18	13
Survivors number (operating from 2010 to 2021)	16	17	13
Supply chain structure	Coal supply chains that include only production links: exploration and extraction preparation, extraction and beneficiation	Coal supply chains grouped around a decision-making center with supporting functions: marketing, logistics, transport etc.	Coal and non-coal supply chains (energy, metallurgical, cement) subordinated to a decision-making center with back-office functions: R&D, marketing, logistics, transport etc.
VC scheme			
Organizational structure	Autonomous non-specialized companies	Group of non-specialized transaction-dependent from acquiring companies – sales and management centers in the form of a large management or large mining company	Closed, vertically integrated structure based on commodity integration of non-autonomous companies forming specialized supply chains within the vertical structure (energy, metallurgy, coke and chemicals, cement)
VCs examples	LLC (OOO) open-pit mine “Kaichakskiy-1”; JSC (AO) open-pit mine “Kanskiy”; FSUE SS (FGUP GT) Arktikugol; OJSC (OAO) mine “Ugolnaya”	LLC (OOO) “SIBUGLEMET holding”; JSC (AO) “SDS-Ugol” holding company; LLC (OOO) “Kolmar coal mining company”	JSC (AO) Siberian Coal Energy Company (SUEK); PJSC (PAO) Severstal; PJSC (PAO) Mechel; EN+ GROUP; JSC (AO) “Sibirskiy cement” holding company

Source: compiled by the article authors basing on the Gereffi, 2005 adapted scheme, CCA FEC data, and electronic accounting and inventory system database.

After dividing companies into VCs types, general stress resilience, robustness and flexibility indices were calculated for each group. Table 2 below and Fig. 1 show the dynamics of the general stress resilience, robustness and flexibility indices from 2010 to 2017 and from 2018 to 2021.

The above data clearly shows that the overall stress resilience, robustness, and flexibility of all types of VCs decreased during the second wave of crisis from 2018 to 2021, suggesting that all selected strategies need to be adjusted to maintain competitiveness and survival. Whereby hierarchical VCs, especially those with energy-carbon specialization, fared worst in terms of stress resilience.

To assess the obtained results, the index value was compared with the companies information received from the experts. This allowed to reconcile the obtained data, to establish a correspondence between the VC type and the business model of the constituent companies, and to evaluate and explain the dynamics of stress resilience of VCs in the coal industry in the long run.

4. Russian coal industry VCs business models and survival prospects under sanctions

The market of VCs in the domestic coal industry is represented by small, autonomous, non-specialized companies (without a main customer). In general, these companies are unstable, their life cycle is much shorter than the average 15-year investment cycle of the coal industry and is about 5 years. Of the 79 companies assigned to this type, only 16 (less than 10 %) operated continuously throughout the analysis period. Most have low profitability or do

Table 2

Stress resilience dynamics indices of the main Russian coal companies VCs types from 2010 to 2021

Specialization and VC type	2010–2017			2018–2021		
	General β_{rescom}	Robustness β_{res}	Flexibility β_{rec}	General β_{rescom}	Robustness β_{res}	Flexibility β_{rec}
Metallurgical and coke-chemical hierarchical	−0.04	0.18	−0.16	0.07	0.05	−0.05
Energy-coal hierarchical	5.23	13.74	-0.11	−5.01	−0.06	−1.80
Cement hierarchical	1.59	0.62	1.93	0.28	−1.02	1.80
Non-specialized “aggressive”	2.68	3.94	1.30	1.22	−0.10	0.61
Non-specialized market	0.62	0.78	0.45	12.18	0.53	3.61

Source: the authors' calculations based on the CCA FEC data.

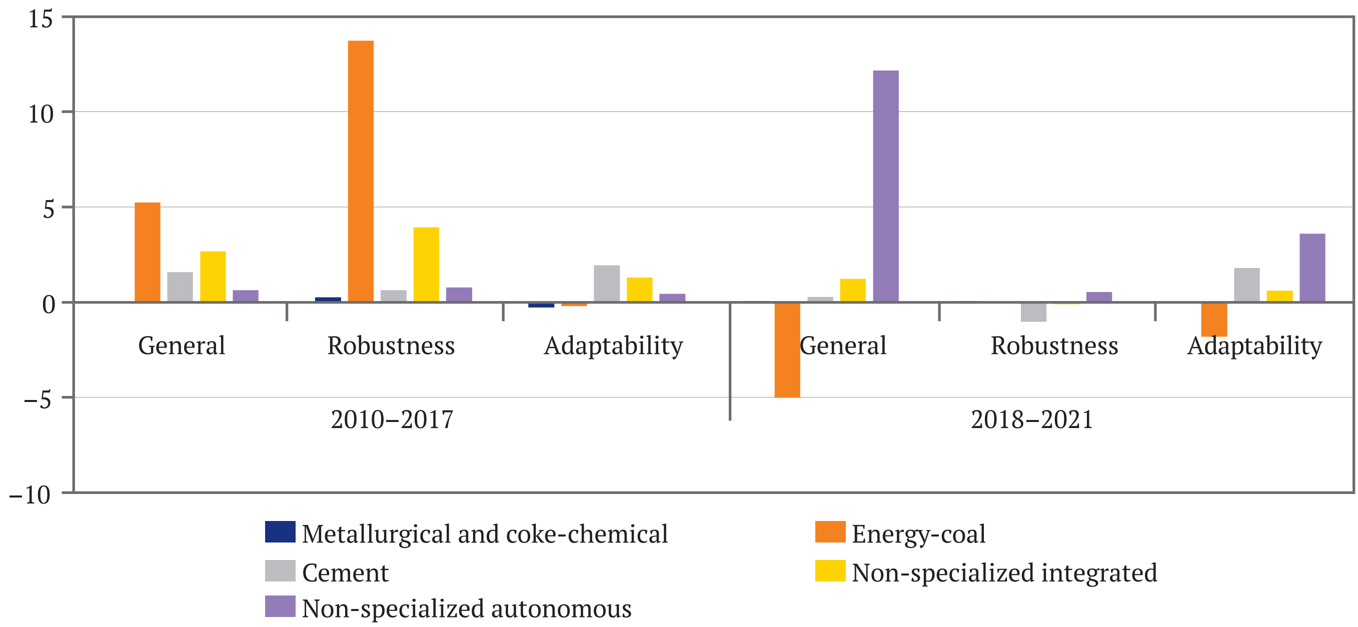


Fig. 1. Stress resilience dynamics indices of the main Russian coal companies VCs types from 2010 to 2021 (Source: authors' calculations based on CCA FEC data)

not cover their costs at all. Thus, according to CCA data, in 2020, at the height of the second wave of the crisis, only 12 companies that constituted market VCs were profitable, with profits in many cases supported by government contracts. It is significant that by 2021, 4 of these 12 companies had already filed for bankruptcy. These data suggest that the majority of autonomous companies follow a survival strategy: enter the market quickly during the boom phase of the industry and exit quickly when the market situation deteriorates. Some companies join formal and informal intermediary VCs during the boom to access the external market to balance sales volume.

The survival strategy in particular explains the unusual current stress resilience indices dynamics of such companies. The relatively low stress level of 0.62 between 2010 and 2017 rose sharply to 12.18 between 2018 and 2021. This is due to the fact that the recovery from the first wave of the crisis in 2013–2017 was due to the production growth of large companies due to increased demand in external markets. Under these conditions, the autonomous companies market niche was small and did not allow the necessary flexibility. During the second wave shock in 2020–2021, on the contrary, the production recovery was driven by the increase of supplies to domestic markets and by autonomous enterprises. The large integrated companies followed a more restrained policy regarding production output and less increased coal production.

It is also important to note that despite these impressive positive dynamics, the absolute increase in output at the expense of autonomous companies has been small, so they can hardly be considered as a stabilization and growth base for the stress resilience of the industry as a whole. It is also of importance to stress that the market companies independence was often purely formal. As part of the survival strategy, they often resorted to all sorts of informal cooperation strategies: they entered into supply contracts with each other, entered and exited the intermediary and hierarchical VCs, actively used state support, and participated in the fulfillment of state contracts. It is also important to note that it was the market VCs that used bankruptcy procedures for the survival purpose in order to reduce credit obligations. Assessing the prospects of VCs in the context of the coal embargo, we can see that while they have provided relatively high current resilience for the coal industry in 2018–2021, they are unlikely to be able to accomplish this task on their own in the long term beyond transparent collaboration with other companies.

The authors of the article refer to the intermediary VCs formed by companies of different sizes, grouped around distribution and management centers, in which function the management or large mining companies that operate in both foreign and domestic markets. They act as an integrative center to which decision-making functions are attributed and provide financial, logistics, marketing and transportation services to their affiliated companies. The relationships of intermediary VCs are based on the integration of commodities (sale of similar commodities), so the integration itself is unstable – it is a conglomerate, but more stable than the market VC. Entering the market through a central distribution company allows intermediary VCs companies to diversify sales and make demand for mined coal more stable, better control prices, and reach a wide range of large consumers, including those abroad. Thus, over the 2010–2021 period, despite changes in the composition of firms included in certain intermediate VCs, only 1 in 18 VCs ceased to exist.

The stress resilience indices dynamics of this VCs group is interesting, as it is opposite to the market VCs. Stress resilience was relatively high in the crisis first wave and fell sharply in the second. This is largely due to the maintaining competitiveness strategy, which was resorted to by the intermediary VCs companies. Between 2010 and 2017, they pursued a new business acquisition (incorporation into VC) and maintaining the core strategy of VCs, which consists of the most profitable companies with premium coal qualities. The purpose of acquiring new assets was to ensure control over the market. Such strategy was especially “successful” at the domestic market. The VCs stress resilience of at the first stage was largely ensured by the state support. Non-specialized conglomerates were created with the participation of both private companies and state institutions for development. Examples of the latter are ROSATOM and the Irkutsk Region Development Corporation. However, commodity integration and dependence on the parent company did not allow the companies that were part of the intermediary VCs to maintain long-term stress resilience, which hit them during the second wave of the crisis.

In assessing the intermediary's business strategy VC and the prospects for its long-term stress resilience, it is important to note that many of the risks associated with market VCs remain unaffected. Market VCs stress resilience decreases sharply during a recession but recovers more quickly during a revival when profits grow faster than costs. At the same time, both the current and long-term stress resilience is lower and decreases faster if a large extractive company acts as a sales center. This can be explained by the fact that the position of the small, non-autonomous firms included in the intermediary VCs is similar to that of the autonomous firms: They stabilize the market for the parent company by reducing risks and costs during a recession, and easily join the VCs and ramp up production during the recovery. But the small companies bear the risks and costs. This was especially evident during the second wave of the crisis, when the parent companies chose the strategy of discarding the problem companies that had been added to the conglomerate during the period of price decline and, on the contrary, actively adding new small companies during the period of price increase. It can be said that the survival strategy during the crisis and the stress resilience of the intermediary VCs, just like the stress resilience of the market VCs, were maintained at the expense of the instability of their constituent firms. The difficulty of implementing such a strategy during the crisis second wave led to a decrease in all stress resilience coefficients. Under the conditions of the embargo on coal supplies, this trend is expected to continue and VC this type of stress resilience as well as its total number may be further reduced. This is likely to lead to an increase in the unstable market VCs number formed due to the cooperative links breakdown. Nevertheless, according to the authors, in this case we can expect less sanctions negative impact on this segment of the coal industry.

The group of hierarchical VCs included specialized closed vertically integrated holdings organized on the additive manufacturing basis. The group included a 13 VCs sample. Unlike the first and second groups, such VCs have a wide range of auxiliary services and productions: human resources services, in-house research and education facilities, service, engineering, transportation, logistics, distribution, and financial units that enable them to effectively manage personnel, keep companies resilient over the long term through technological innovation, market and distribution management, and optimize logistics plans and save on transportation costs. Finance and sales departments coordinate and control the company's business units activities and act as the decision-making center.

Sales diversification and supply large scale play a significant role in the hierarchical VCs sustainability. Most of the systemically important coal companies form part of the hierarchical VCs. The monopoly position in the market allows companies to react flexibly to external and internal shocks, including at the expense of production volume reduction. Own transport and logistics system allows companies to even out market fluctuations and to shift supplies from one market to another. The values of stress resilience coefficients show that companies have chosen the optimal business strategy in the period from 2010 to 2017: diversification of sales and deliveries on a significant scale provided the ability to absorb external and internal shocks (the robustness coefficient β_{res} was the highest – 13.74). However, already in this period hierarchical VCs were characterized by low flexibility (the adaptability coefficient β_{rec} was negative – −0.11). A significant role in ensuring companies stress resilience was played by their status of systemically important companies and close contacts with federal and regional authorities. However, during the second wave of the crisis, as the influence of distributed production targeting resources with predetermined characteristics greatly increased, the stress resilience of hierarchical VCs began to falter. Their closed nature, dependence on external markets, and desire to amortize the effects of the crisis by controlling output and prices led to a sharp decline in overall stress resilience. The general stress resilience index β_{reccom} dropped 10 units at once, from 5.23 to −5.01.

The analysis showed that the strategy choice and long-term stress resilience of hierarchical VCs directly correlate with the specialization of chains. Thus, companies representing metallurgical and cement holdings had low stress resistence during both periods (close to the industrial average). This occured mainly due to the coal companies subordinate position within the holdings, their strict peg to the major consumer and financial flows redistribution in favor of the main, non-coal production. During the first wave of the crisis, metallurgical and cement companies adapted more easily to the price reduction due to the relatively low cost of coal production and reduced coal production volumes less than the industry average. The constituent companies were the lowest non-autonomous link of the VCs, strictly tied to specific metallurgical or cement companies. The internal supply chains were part of a diversification policy based on commodity integration, and a means to protect against falling revenues in times of crisis. Metallurgical and cement VCs managed to retain their coal assets.

On the contrary, during the crisis wave of 2018–2021, when production costs approached the industry average, these companies were forced to divest non-core coal assets to reduce costs. In addition, it was during the second wave that distributed production began to actively penetrate the metallurgic and cement industries. VCS set increasingly stringent requirements for metal and cement with specified properties, and accordingly the requirements for coal quality became more stringent. Previous coal assets did not always meet these requirements, and commodity integration as a tool to diversify activities and hedge against risks no longer fulfilled its role. It is significant that companies did not abandon their coal plants during the recession, but during the recovery period when prices and demand for coal were rising rapidly.

As an example, we can cite the Severstal and EVRAZ VCs. In early December 2021, Severstal Mining and Metallurgical Company shareholders signed a binding agreement with Russkaya Energia LLC to sell Vorkutaugol. In December 2021, EVRAZ transferred its coal assets (seven mines, two open-pit mines and three ore-processing plants in the Kemerovo Region and one mine in the Tuva Region) to Raspadskaya Coal Company and began the process of separating it into an independent business[1]. The sanctions imposed on EVRAZ shareholders put this process on hold. Nevertheless, we can state that the coal assets partial denial allowed the metallurgical VCs to recover faster in the face of the revival and keep the value of the general stress resilience index in 2018–2021 within the positive limits of 0.07 and 0.28, respectively. However, these values are small, given the distributed production expansion and the uncertainty of the metallurgical VCs long-term strategy, they are unlikely to cover the negative stress resilience of all specialized VCs, especially energy-coal, which suffered the greatest decline in coal demand. All this leads to the conclusion that cooperation ensures the maintenance of a higher level of current stress resilience of VCs, but in the long run, the maintenance of current business strategies of metallurgical VCs may lead to their reduction.

Unlike metallurgical and cement VCs, energy-coal VCs have always focused on global coal markets; therefore, coal mining companies and divisions have played and continue to play a leading role. The control center and the financial center are often located in the company coal mining or sales divisions. The cooperative strategy implementation made it possible to accumulate and redistribute an income considerable part in favor of the coal division and actively develop it. This ensured a high level of stress resilience for the energy and coal holdings in 2010–2017. The general stress resilience and robustness coefficients in this group of companies were the highest in the industry, 5.23 and 13.74, respectively. However, the dependence on foreign markets meant that already in the second wave of the crisis all coefficients became negative and the overall stress resilience became the lowest in the industry – 5.01. Under the Russian coal embargo, the energy-coal VC strategy is the most vulnerable, and the positive effects of the cooperative strategy can hardly offset the negative effects of reduced foreign demand. In the long run, therefore, we can expect a further decline in both current and long-term stress resilience, which could lead to the closure of some companies that are part of the energy-coal VCs, which is unacceptable given the share of systemically important companies in energy-coal VCs and the possibility that VCs will morph into a simpler relational and market-oriented form.

Conclusion

The analysis conducted has shown that the coal industry is in a difficult situation, the stress resilience of its key segments is low, tends to decrease and will only decrease in the future. In the most difficult situation are the systemic companies within the hierarchical VCs, especially the energy-coal companies, which were mainly focused on external markets, the cooperative survival strategy does not even provide support for the current stress resilience. Market and relational VCs are in a more favorable position. However, the indicator of coal production volume, the volatility of VCs, are not able to provide reliable development of the coal industry. All this suggests that part of the coal companies will inevitably close and the other part will need deep restructuring. At the same time, the current survival strategies of companies do not allow them to solve this problem alone and require the active participation of the state. In the initial phase, government support can be aimed at maintaining demand for coal for systemically important companies by redirecting coal exports eastward through transportation infrastructure development, but in the long term, stress resilience of VCs and the coal industry as a whole can only be ensured by developing cooperative relationships based on technological integration with long-term government sup-

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port. This integration can be based on promising low-carbon energy technologies focused on the production of blended fuels with specific properties; digital technologies that ensure efficient logistics and maintenance of safety; robotic equipment that guarantees safety and high productivity thanks to internal collaboration with engineering companies. Precisely these technologies will make cooperative links more sustainable and the cooperative strategy less costly and more efficient. Such an approach, according to the authors of the article, will initiate the introduction of decentralized production elements in coal VCs and ensure the industry's development and stress resilience in the long term.

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