NON-LINEAR SPATIAL DYNAMICS OF METHANE RELEASE IN UNDERGROUND BOREHOLES FOR SUSTAINABLE MINING PRACTICES

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https://doi.org/10.5281/zenodo.14685797

ARTICLE INFO

Qabul qilindi: 10-Yanvar 2025 yil
Ma’qullandi: 15- Yanvar 2025 yil
Nashr qilindi: 18- Yanvar 2025 yil

KEY WORDS

methane from coal seams; methane reservoir; mine gas; coal deposit; gas drainage efficiency; sustainable geotechnologies; longwall.

ABSTRACT

This paper addresses the challenge of enhancing energy efficiency in the utilization of methane from coal mines to support the sustainable development of geotechnologies, particularly in the transition to cleaner, resource-efficient energy production. This issue is critical because the anthropogenic impact of methane emissions from coal mines on global climate change is 21 times greater than that of carbon dioxide. Coal seams rich in gas and the adjacent rocks are to be classified as technogenic coal-gas deposits, with the extracted gas viewed as an alternative energy resource. Current methods for managing coalmine methane require improvement, as the existing "mine-longwall" approach does not adequately consider the spatial and temporal specifics of the production face's advancement. This gap is particularly relevant in the context of environmentally friendly coal mining. The aim of this study is to uncover patterns that illustrate the non-linear dynamics of methane release in underground boreholes, thereby fostering the sustainable development of geotechnologies through improved quality of the extracted methane-air mixture.

Introduction: In our country, addressing coalmine methane issues is particularly crucial as we strive for a "transition to clean, resource-efficient energy production and enhanced mining efficiency," which is a key objective in the Russian Federation's scientific and technological development strategy. This aligns with a progressive global trend toward incorporating elements of a "green economy" in underground geotechnologies to facilitate "sustainable mining." Essential components of sustainable development in green mining encompass integrated subsurface development under the "Industry 4.0" initiative, fostering a resourceful environment, and implementing energy conservation measures within the mining sector. The environmental focus of mining is hindered by the lack of a comprehensive view of methane, not just as a greenhouse gas but also as a potential internal source for boosting coal mining profitability. Utilizing methane in gas reciprocating units for power and heat generation can enhance the energy efficiency of mining operations while significantly reducing coal extraction costs. Current safety regulations prohibit the operation of local gas drainage networks when gas concentrations in the mixture fall below 25%. Moreover, the failure of a single borehole, particularly in the wellhead area, can create an aerodynamic connection to the mine atmosphere, posing serious safety risks and challenges to environmentally balanced resource management. By considering the interaction of geomechanical factors in 3D models of rock strata displacement, it becomes possible to predict the distribution of methane release throughout the surrounding coal-rock mass, although its non-linear aspects are only partially captured.

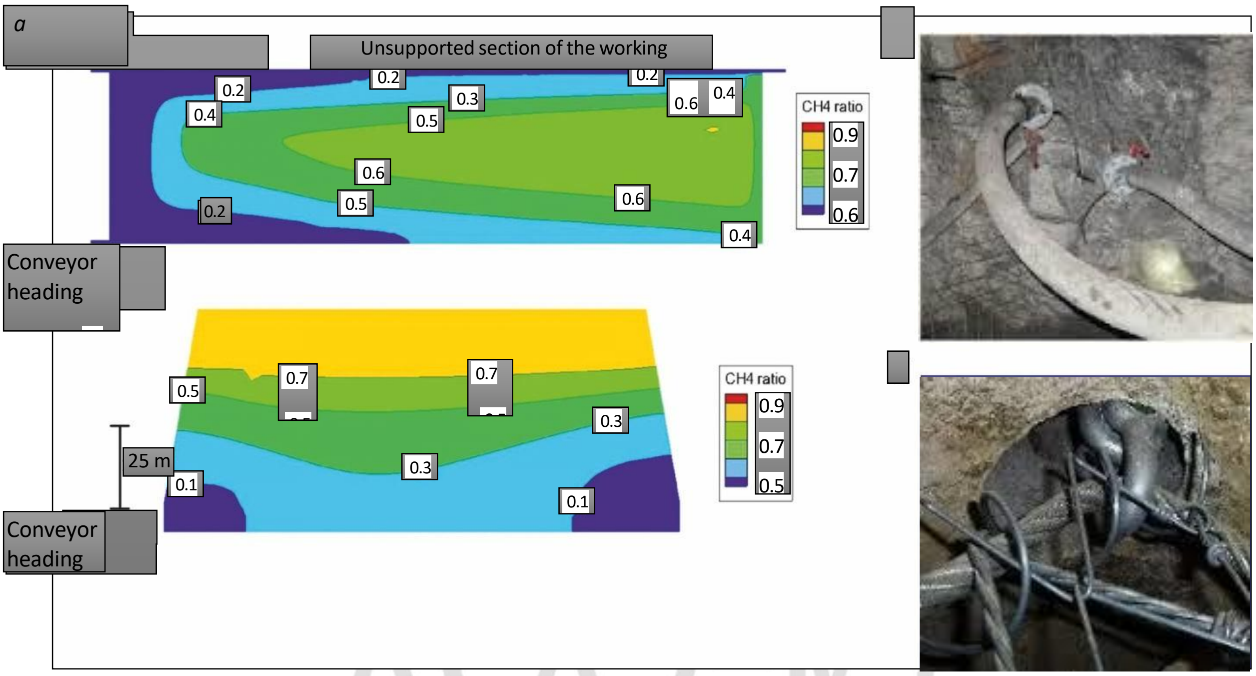

Fig.1. Results of modeling distribution of permeability and methane concentration in the undermining coal-rock mass [39]:a is the distribution of methane concentration along the extraction column (top view); b is longwall section view; c is horizontal permeability variation in the longwall plane and 60 m behind the longwall (gob area); d is the distribution of vertical permeability variation 60 m behind the longwall (gob area)

The most significant international research on this topic includes studies by H. Guo, L. Yuan, and B. Shen, who employed experimental and analytical methods to model geomechanical and aerogas processes (see Fig. 1). Their findings indicate that abutment pressure can extend up to 300 meters ahead of the production face. The displacement of overlying strata leads to increased stratification and fracture formation within 170 meters behind the longwall, with the height of the man-made gas reservoir potentially reaching 145 meters from the bottom to the top of the seam. In this area, the stress level is considerably lower than in the abutment zone, resulting in enhanced methane release. One study developed a flow model for the methane-air mixture, accounting for deformation processes in the rock surrounding the gas drainage borehole. This model considers various factors—including gas sorption, coal porosity, sealing depth, and air inflow—that influence methane concentration in the extracted mixture. Both foreign and Russian researchers have reported on methane release dynamics based on measurement time, distance from the longwall face, and extraction column length. However, a major limitation of many models is their inadequate consideration of the time factor and the varying geomechanical conditions of coal mining. This oversight restricts the identification of the non-linear aspects of deformation processes, ultimately diminishing the accuracy of methane release dynamics models. Prominent studies by Russian researchers in this field include works. One study focused on developing a theory regarding the energy potential of coalmine methane, linking its release dynamics to non-linear elastic pendulum-type wave manifestations in the coal-rock mass. This research line necessitates the advancement and validation of theoretical and experimental models that can reliably capture non-linear dynamics and distinguish them from fluctuations and induced components related to production face advancement. Consequently, this study is based on the hypothesis that "non-linear stress-strain states in the surrounding rock mass—triggered by the spatial and temporal advancement of the production face—induce transformations in metastable gas-coal solutions and generate methane concentration waves that may shift depending on the distance to the longwall face and the span of the main roof. Identifying the specific characteristics of methane concentration wave arrangements in underground boreholes is essential for advancing sustainable underground technologies in deep gassy coal seam development. Therefore, the research focuses on the unique non-linear aerogas conditions in gas drainage boreholes caused by stress relief waves and roof rock displacement. The operational reliability of local gas drainage networks is crucial for utilizing coalmine methane as fuel for gas reciprocating units in cogeneration plants. This highlights the need for a comprehensive program aimed at ecological transformation and improved energy efficiency in the mining sector. Thus, the objective of this work is to identify patterns that illustrate the non-linear dynamics of methane release in underground boreholes to support sustainable geotechnological development.

Materials and Methods: Most researchers have established patterns and semi-empirical relationships describing methane release dynamics or borehole spatial arrangements (distances to specific benchmarks or to the face line). However, the existing body of results does not sufficiently capture the overall mechanism of the studied processes. Challenges in formulating the problem and a narrow approach to its resolution limit the ability to visualize a four-dimensional space (including time) on a two-dimensional plane, significantly constraining potential solutions. Issues concerning the spatial distribution of parameters—such as the coefficient of equivalent stress concentration in the rock mass, wind speed, or frequency-directed wave spectrum—have been partially addressed in related fields. For instance, the stability of mine workings has been successfully maintained using 3D modeling based on the finite element method in various software packages. Nonetheless, the limitations of this approach are similar to those identified in previous studies, including a static portrayal of the process, first-order considerations of horizontal permeability in the overlying rock mass, a lack of accounting for the non-linear nature of geomechanical processes and their impact on permeability, 2D interpretations of observed displacements in roof rock layers, and irregular methane release over time. In hydrometeorology, reanalysis data from NCEP/NCAR Reanalysis1 has been utilized for spectral hydrodynamic modeling of wind wave parameters, complemented by comparisons to field observations through regression analysis in 2D. This approach limits the applicability of the results. A more effective method is to approximate spatial and temporal variables using Fourier series, as demonstrated in optimization problems in ore dressing.

The observed data were interpreted using local polynomial regression (LOESS) to identify the best-fitting function amidst widely scattered data. Incomplete sampling was refined using 3D interpolation techniques (such as Akima, Preusser, Renka, and Watson). Optimization procedures were selected based on their determination coefficient to ensure the fitted surface closely matched the original data. The most accurate results were achieved with the Watson algorithm, which uses a circular aerial base for interpolation, and the Renka algorithm, which employs a standard triangulation method. One study reported wave variations in methane concentration in gas-drained rock masses during the extraction of a seam with a methane content of up to 23 m^3/t daf. In longwall coal mining, cross-measure boreholes were drilled toward the production face every 25 meters, with 6-8 boreholes operating simultaneously. This research revealed the non-linear nature of methane concentration variations during the gas drainage of rock masses using boreholes with consistent spatial orientation. This phenomenon was observed behind the longwall and more than 45 meters ahead of the face line. However, a limitation of this work was the lack of a method to visualize the 3D spatial distribution of gas flows. Consequently, experimental datasets were processed to create "isogas" surfaces in 3D, reflecting the dynamics of methane concentration relative to the distance from the face line and the wellhead location concerning the extraction block's beginning. Measurements at each borehole's wellhead were conducted using standard procedures with Dräger X-AM 2500 gas analyzers, which were occasionally verified against SHI-12 interferometers, showing deviations of no more than 10%. For the first time, in spatial-temporal studies of methane concentration dynamics (in the CH4-S plane), the distance from the longwall (L) was introduced, enabling the creation of a function space for the analyzed process (CH4 as a function of S-L).

Conclusions. Based on the study results, the hypothesis regarding the wave like nature of methane release has been validated. The following conclusions can be drawn:

- Increasing the main roof span from 17 to 80 meters, along with reducing the distance to the face line (in front of the longwall) from 110 to 30 meters, leads to a non-linear polynomial rise in methane concentration in underground boreholes from 13% to 33%.
- An increase in the roof rock span from 10 to 70 meters results in a rise in the local maximum of methane release occurring 70-90 meters ahead of the face line, indicating that aerogas conditions in the gas drainage system require improved management.
- Current geotechnologies for developing deep-lying gassy coal seams, coupled with operational management of the local gas drainage network, do not ensure a safe methane concentration level (≤ 25%) in the withdrawn mixture when the distance to the longwall face is ≤ 20 meters. The proposed approach to 3D data visualization can enhance the precise mapping of spatial gas content distribution within coal seams (as an addition to GIS [33]) or the specific characteristics of hydrocarbon potential in tectonic screen traps [37].

Therefore, to improve technologies that ensure the reliability of gas drainage systems and enhance the quality of the withdrawn methane-air mixture, applying the identified patterns and quantitative characteristics is particularly important

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