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Experimental study on forced ventilation in dead-end mine working with various setbacks of the ventilation pipeline from the working face

A. A. Kamenskikh, G. Z. Faynburg, M. A. Semin ✉, A. V. Tatsiy

Mining Institute of the Ural Branch of the Russian Academy of Sciences, Perm, Russian Federation

✉ *seminma@inbox.ru*

Abstract

The study of airflow patterns at the ends of dead-end mine workings is crucial for optimizing underground mining ventilation systems. Understanding these patterns forms the basis for designing and implementing effective ventilation strategies.

Previous studies have shed light on the behavior of the main vortex and the formation of stagnant zones in such environments, but these insights remain fragmented and call for a more systematic exploration to integrate them into a comprehensive theory.

This paper presents the results of a thorough field investigation into the forced ventilation behavior in a dead-end mine working with a significant cross-sectional area (29.2 m^2). We evaluated the impact of varying the setback distance of the ventilation duct's end from the working face at intervals of 10, 15, 17, 19, and 21 m. The experimental design included precise measurements of turbulent airflow velocities at 25 carefully chosen points (in a 5x5 grid) for each setback distance, covering the area from the working face to beyond the end of the ventilation duct. This included additional measurements taken 1 meter and 10 meters past the termination of the ventilation duct, moving towards the entrance of the working area.

The fieldwork was carried out in a typical dead-end stope at the Kupol gold-silver mine in the Chukotka Autonomous District, created by drilling and blasting.

The volume of fresh air delivered to the working was maintained at a consistent rate of 17.4 m^3/s across all scenarios, aligning with the mine's standard air flow rate derived from the ventilation requirement for exhaust gases emitted by internal combustion engines of Load-Haul-Dump (LHD) machinery. With the duct's terminal cross-sectional area at 0.8 m^2, this resulted in an inflow velocity averaging 21.75 m/s.

Additionally, we included insights from three-dimensional numerical simulations performed in ANSYS Fluent, focusing on steady-state air movement and developed turbulence within the dead-end space. A comparative review of both empirical and modeled data shows that the ventilation jet, for all tested setback distances up to 21 m, successfully delivered air to the working face, where it then dispersed and initiated reverse flow patterns.

These experiments led to the formulation of a linear relationship between the maximum relative velocity (compared to the initial jet velocity) at a distance of 1 m from the working face and a key geometric factor of the ventilation setup. This factor is the ratio of the duct's setback distance to a characteristic dimension of the cross-sectional area, calculated as the square root of the cross-sectional area.

Keywords

mine ventilation, dead-end face, forced ventilation, ventilation pipeline setback, field experiment, numerical experiment, airflow structure

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ТЕХНОЛОГИЧЕСКАЯ БЕЗОПАСНОСТЬ В МИНЕРАЛЬНО-СЫРЬЕВОМ КОМПЛЕКСЕ И ОХРАНА ОКРУЖАЮЩЕЙ СРЕДЫ

Научная статья

Экспериментальные исследования проветривания тупиковой выработки нагнетательным способом при различном отставании вентиляционного трубопровода от груди забоя

А. А. Каменских, Г. З. Файнбург, М. А. Семин ✉, А. В. Таций

Горный институт УрО РАН, г. Пермь, Российская Федерация

✉ *seminma@inbox.ru*

Аннотация

Исследование структуры вентиляционных потоков в призабойной части тупиковой выработки является важным элементом при целенаправленном управлении ее проветриванием и обеспечении безопасности ведения подземных горных работ. Ранее проведенные исследования показывают, что, несмотря на общее понимание протекающих в тупиковой выработке процессов возникновения основного вихря и застойных зон, полученные результаты носят фрагментарный характер и без дополнительных исследований практически не поддаются единому концептуальному обобщению.

В статье приведены результаты детального натурного эксперимента по исследованию процессов нагнетательного проветривания тупиковой выработки большого сечения (29,2 м^2) с пятью различными вариантами отставания конца нагнетательного вентиляционного трубопровода от груди забоя: 10, 15, 17, 19 и 21 м. Для каждого варианта в соответствии с разработанной методикой эксперимента производили замеры скорости турбулентного вихревого воздушного потока в 25 различных характерных точках (сетка 5х5) в каждом сечении тупиковой горной выработки, которые выбирали через каждый метр от груди забоя до конца вентиляционного става, а также дополнительно еще через 1 м и еще через 10 м от конца вентиляционного става к устью выработки.

Исследования проводили в стандартной тупиковой очистной выработке, проходимой буровзрывным способом, на золотосеребряном руднике «Купол», расположенном в Чукотском автономном округе.

Расход подаваемого в выработку свежего воздуха во всех случаях сохраняли постоянным и равным типичному для рудника расходу 17,4 м^3/с, определяемому расчетным значением по фактору проветривания выхлопных газов от двигателей внутреннего сгорания погрузочно-доставочных машин. При площади сечения конца трубопровода 0,8 м^2 это дает среднюю скорость поступающей струи в 21,75 м/с.

Данные натурного эксперимента дополняли результатами трехмерного численного моделирования в вычислительном пакете ANSYS Fluent. Исследовали стационарное движение воздуха в тупиковой выработке в режиме развитой турбулентности. Сравнительный анализ полученных результатов натурного и численного экспериментов убедительно показал, что во всех исследуемых случаях отставания (не более 21 м) вентиляционного трубопровода от груди забоя вентиляционная струя, выходящая из вентиляционного трубопровода, достигает груди забоя, а затем разворачивается вдоль него с различной интенсивностью и формирует обратное движение воздушного потока из тупика.

Полученные результаты позволили получить линейное уравнение связи между максимальной относительной (к начальной скорости струи) скоростью на расстоянии 1 м от груди забоя и основного геометрического фактора зоны проветривания – отношения длины отставания конца трубопровода к характерному поперечному размеру – корню квадратному из площади поперечного сечения.

Ключевые слова

рудничная вентиляция, тупиковый забой, нагнетательный способ проветривания, отставание вентиляционного трубопровода, натурный эксперимент, численный эксперимент, структура воздушных потоков

Финансирование

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Introduction

Ensuring the reliability of effective ventilation within dead-end workings of mines represents a paramount concern in the domain of mine ventilation, governed by the regulatory frameworks of safety in underground mining operations[1]. This issue garners significant attention from both domestic [1–3] and international [4–6] researchers, as evidenced by an extensive body of literature. The scholarly discourse encompasses an array of topics, including the peculiarities of ventilating dead-end workings across various mining methodologies [7, 8], as well as the issues of aerological process modeling within such environments. This entails the judicious selection of turbulence models [6] and the employment of discrete modeling approaches [9]. Research has delved into several exacerbating factors, such as the persistent dust emission during the operation of mining combines [10], gas emission within the excavated spaces [8, 11], and the analysis of oxygen transfer as a distinct component of the atmospheric milieu [5]. The literature also explores diverse criteria for assessing the ventilation efficiency of dead-end workings [4].

A critical facet of optimizing the ventilation of dead-end workings lies in the selection of ventilation methodologies and equipment parameters, including the placement of the ventilation pipeline and the regulation of airflow within [12]. Among the prevalent practices in this realm is the application of forced ventilation, characterized by the generation of an active air jet delivered via a pipeline. The terminal segment of this pipeline is intentionally positioned a specified distance from the working face, either to accommodate operational exigencies or to comply with safety regulations [6, 13].

The principal geometric determinants of the ventilation zone's volume (V) are the working's height (H) and width (B) – that is, the effective scale of the cross-sectional area (S) – as well as the distance by which the end of the ventilation conduit is set back from the working face (L). This distance shapes the overall configuration of the ventilated space [14]. Let us define the form factor of the ventilated object as the dimensionless measure of the setback distance of the pipeline's end from the working face, expressed in units equivalent to the square root of the cross-sectional area $f = L/\sqrt{S}$.

The calculation of the ventilation zone's volume is contingent upon the specific variables and context, with V equating to either $H \cdot B \cdot L$ or $S \cdot L$. Alternatively, it may be approximated to the volume of the flue gas exhaust zone, as ascertained through the application of empirical data and analytical methods.

The efficacy of ventilation and the balance between the processes of contaminated air displacement and its mixing with fresh air are fundamentally determined by the flow rate of fresh air (Q_0) allocated for ventilation purposes. This flow rate, in conjunction with a specified pipeline diameter (d) or cross-sectional area (s) dictates the average velocity (U_0) of the ventilation jet. This jet, in turn, shapes the flow structure within the dead-end working, influenced by the degree of jet constriction, $F = s/S = (d/D)^2$, which varies between 0 and 1, alongside various other factors that govern the balance between displacement and mixing processes within the ventilated area.

The primary metric of ventilation effectiveness is the air quality at the working face under all conditions, and in the context of non-steady-state scenarios, it is the duration required for ventilation to clear contaminants, such as flue gases following drilling and blasting operations. The determination of the requisite fresh air flow rate is predicated upon achieving designated air quality benchmarks.

Given the complexity of flow dynamics and the indeterminate nature of the ratio between displacement and mixing processes, accurately gauging the actual ventilation duration is feasible solely through comprehensive, field experimentation.

In practical terms, for determining the ventilation duration, practitioners rely on the estimated air exchange time (τ) for a specific volume of contaminated air (V) expressed as

$$\tau = \frac{V}{Q}, \quad (1)$$

where Q is the rate of air supplied to the ventilated volume V.

The minimum time required to ventilate the face is realized when ideal displacement (advective transfer) processes dominate within the ventilated zone, as determined by Equation (1). Conversely, in scenarios where ideal mixing processes (thorough mixing, dilution) prevail, coupled with the presence of stagnant zones, the theoretical ventilation duration for a dead-end face is effectively infinite. The actual ventilation timeframe spans these broad extremities.

A crucial prerequisite for preventing stagnant zones at the working face and ensuring the dominance

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[1] Uniform safety rules for developing ore, nonmetallic and alluvial deposits by underground mining. Appr. by Gosgortechnadzor of the USSR on 21.10.1954, Moscow: Gosgortekhizdat, 1959.

Federal Rules and Regulations in Industrial Safety "Safety rules in mining works and processing of solid minerals", appr. on 08.12.2020, No. 505. Electronic text. CODEX Consortium. Electronic Fund of Legal and Regulatory Technical Documentation: official website. URL: https://docs.cntd.ru/document/573156117 (date of access: 20.06.2023).

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of displacement processes is the generation of an active jet. To this end, the jet must maintain its integrity over a distance (L_{eff}) greater than the setback from the working face (L) thereby actively "sweeping" over the working face to facilitate the efficient removal of gassed and dusty air from the vicinity of the face and the face itself. This criterion can be articulated as

$$L < L_{rated} < L_{eff}, \quad (2)$$

where L_{rated} is the maximal permissible setback distance as prescribed by safety regulations.

Therefore, analyzing the flow structures in the proximity of the working face within a dead-end working is imperative for the deliberate design of its ventilation system. This analysis underscores the significance of the effective range of the jet, L_{eff}, the setback of the pipeline's end from the working face L and the flow rate of fresh air supplied Q_0 the cross-sectional dimensions of both the working and the pipeline.

Foundational Concepts of Airflow Patterns in Dead-End Workings with Forced Ventilation

Over half a century ago, significant advancements in the study of ventilation within dead-end mine workings (also known as airless ends) were made I.A. Shvyrkov [1], A.I. Ksenofontova [2], V.N. Voronin [3], P.I. Mustel [15], among others [16–18]. These researchers undertook theoretical examinations of jet ventilation in dead-end chamber-shaped workings, establishing foundational concepts on the mechanisms for removing contaminated air from the face through mixing and displacement. Additionally, they elucidated the relationship between the cross-sectional area of the working and the efficiency of jet action [18]. A key formula emerging from their work is:

$$L_{eff} = K\sqrt{S}, \quad (3)$$

where K is a dimensionless proportionality coefficient, determined either experimentally or theoretically, and typically varies widely in practice (from 2 to 8, but most commonly within 3–6) [14]. This variation underscores the dependence of K on other ventilation arrangement conditions and highlights the need for relatively large-scale studies for further elucidation.

This formula (3) can be reformulated as:

$$\frac{L_{eff}}{\sqrt{S}} = k\frac{L}{\sqrt{S}}, \quad (4)$$

where k is a new coefficient related to K by the formula $K = kf$, facilitating the delineation of the form factor f. From this, it can be inferred that $k > 1$.

Notably, for a classical ventilation pipeline setback L of 10 m, the form factor with a working cross-sectional area of 3×3 is 3.33, and for a size of 2×2, it is 5. A setback of 15 m, permissible under current safety regulations for working cross-sections larger than 16 m^2, yields a form factor of $f = 3.75$.

In various international studies [4, 6, 13], formula (3) is presented as

$$L_{eff} = 4\sqrt{S} \quad (5)$$

or alternatively, utilizing the ventilation pipeline diameter d, as

$$L_{eff} = 30d. \quad (6)$$

It's important to note that the concept of jet range, denoted as L_{eff}, while intuitively understood, lacks a formal definition, leading to varied interpretations and the coefficient K in formula (3) fluctuating based on factors like working cross-section, pipeline location, its cross-section, jet velocity, and other ventilation conditions.

The termination of the total air flow rate towards the working face, discounting turbulent pulsations, marks the end of the jet. This distance, denoted as L_{eff}, represents the range the jet "reaches". Defining this distance more rigorously allows for a more precise determination of the airflow rate sufficient for effective ventilation in a given cross-section near the working face. This determined airflow rate, deemed sufficient for effective ventilation at or near the working face, is labeled Q_{face}. It is calculated to ensure that the time required to ventilate the space immediately adjacent to the working face, denoted V_{face}, is less than or equal to the time needed to ventilate the entire face, expressed as:

$$t_{eff} = \frac{V_{face}}{Q_{face}} \le t_{face} = \frac{V}{Q_0}. \quad (7)$$

The area between the working face and the cross-section positioned 1 meter away from it can be selected as the size of the near-face space. This selection is informed by the dimensions of the human breathing zone, defined as a radius of 0.5 meters from the worker's face, in accordance with SNiP 41 01 2003 standards. This distance, leading to the terminus of the pipeline's trajectory related to this area, is denoted as L_1.

The volume of air entering this specified zone can be quantified by referencing the minimum velocity stipulated by safety regulations. The calculation employs the formula $U_{min} = 0{,}1\, P/S$ (m/s), where S represents the cross-sectional area of the working, m^2; and P stands for the perimeter of the working, m. For the conditions outlined in our experiment, this results in a velocity of 0.07 meters per second. It is crucial to underscore that this velocity constitutes merely 0.32% of the initial velocity (U_0 = 21.75 m/s) of the jet as it exits the ventilation pipeline, as evidenced by the data from the comprehensive field experiment.

It's noteworthy that the air velocity detectable by humans and vane anemometers is approximately 0.15 m/s, which corresponds to 0.69% of the initial jet velocity U_0. Furthermore, the traditional minimum velocity prescribed for stopes, fixed at 0.25 m/s, represents 1.15% of U_0. In the context of our field experiment, this implies that the time required to ventilate the space near the face, positioned 1 meter from the working face, amounts to 8 s.

Empirical evidence indicates that the efficacy of the jet within the dead-end (constrained area) is enhanced by enlarging the cross-section of the working. This enhancement is attributed to the ability of the jet to extend over greater distances within larger cross-sectional workings without being impeded by the resistance of the return flow. The occurrence of this return flow within the dead-end is an inevitable consequence, dictated by the principles of mass conservation and the continuity equation.

Previously, the investigation into the complex, three-dimensional vortex-like structures created by forced ventilation methods was hindered by the limited scope of analytical techniques. However, advancements in computational methodologies and the expansion of computer processing capabilities have led to an increased adoption of mathematical modeling tools in a three-dimensional framework. This approach has significantly enhanced research into the ventilation processes within dead-end mine workings, as evidenced by studies [7, 8, 19].

For example, N. O. Kaledina and S. S. Kobylkin [16] leveraged numerical three-dimensional modeling techniques to explore ventilation strategies for dead-end extended workings in gas-rich mines. In such environments, the prevalent release of light, combustible gases poses a considerable risk to mining safety. E.V. Kolesov and B.P. Kazakov [18] applied these numerical three-dimensional modeling methods to investigate the effectiveness of ventilation systems in dead-end mine workings post-blasting operations.

Article [20] explores the ventilation challenges in dead-end mine workings, focusing on the effects of variations in the distance of the ventilation pipeline from the working face and different air jet velocities from the ventilation pipeline on ventilation effectiveness.

This body of research engages in a thorough examination of the selected turbulence models, the methodologies for numerical solutions, and the outcomes achieved, often tailored to a handful of specific scenarios.

The comprehensive review of these studies reveals that while there's a broad consensus on the existence and behavior of primary vortex and stagnant zones within dead-end workings, the findings are somewhat piecemeal. The current understanding and results, though insightful, are not universally applicable or conceptually cohesive without the prospect of further, more targeted research endeavors.

Field experimental data on forced ventilation in dead-end mine workings are notably less prevalent than those obtained from computational experiments, primarily focusing on the duration of face ventilation and the overall penetration of the jet into the dead end.

Historically, a crucial standard[2] or forced ventilation in these settings was to maintain the distance from the end of the ventilation duct to the working face at no more than 10 meters. This standard was suitable for the use of 400–600-mm pipes and low-power fans, which matched the typical dead-end working dimensions of the era, approximately 2 × 2 m in cross-section (with a form factor of f = 5). However, contemporary updates to the regulatory framework, as exemplified by the revised FNiP PB[3], now acknowledge the feasibility of extending this setback up to 15 m from the working face, provided that the face cross-section exceeds 16 m^2 (indicating a form factor of $f < 3.75$).

Despite this regulatory shift, practical implementation often faces challenges, as indicated by safety justifications reviews such as in [18]. These challenges highlight the need for a deeper, scientifically grounded comprehension of the ventilation dynamics within dead-end workings. This is the core focus of the current study.

Below are the findings from comprehensive field research on forced ventilation in dead-end stopes at the Kupol gold-silver mine, specific to its conditions. These are accompanied by selected results from numerical modeling that enhance the insights gained from the field experiment.

Subject of the Field Study

The Kupol mine, situated in the Far North-East of the Russian Federation within the permafrost zone, adopts specific measures to counteract rock thawing and enhance stability. Here, underground workings are ventilated using a forced method, with air entering the mine at temperatures of –20°C or lower, without

[2] Uniform safety rules for developing ore, nonmetallic and alluvial deposits by underground mining. Appr. by Gosgortechnadzor of the USSR on 21.10.1954, Moscow: Gosgortekhizdat, 1959.

[3] Federal Rules and Regulations in Industrial Safety "Safety rules in mining works and processing of solid minerals, appr. on 08.12.2020, No. 505. Electronic text. CODEX Consortium. Electronic Fund of Legal and Regulatory Technical Documentation: official website. URL: https://docs.cntd.ru/document/573156117 (date of access: 20.06.2023).

the need for heating. This location is not considered hazardous in terms of gas or dust presence.

Mining operations, including development, preparatory work, and stoping at the Kupol mine, are executed via the drilling and blasting method. This approach is necessitated by the high strength characteristics of the ores and rocks encountered. Drilling and blasting activities are organized into two shifts per day, incorporating two-hour breaks between shifts and two lunch breaks. During these working shifts, drilling and the transportation of blasted ore take place, while blasting operations are scheduled between shifts and during lunch breaks.

The mining cycle encompasses not just drilling, charging, and blasting of blast-holes, along with the loading and transportation of blasted ore from the face, but also ventilation of the face and ensuring its safety post-operation. High-performance self-propelled equipment is employed for the principal tasks of the drivage cycle.

Dead-end faces at the Kupol mine vary in length from 15 to 150 m, boasting an average cross-section of 29.2 m^2 in the light, and an average advance of 4.2 m per blast. The majority of the blasted ore is displaced by blasting to a range of 10–15 m from the working face, though some fragments can reach up to 40 m, posing a risk to the ventilation pipeline. Consequently, considering the length of the LHD machines with internal combustion engines is about 12 m, it's advisable to maintain a setback of approximately 20 m for the ventilation duct from the working face.

The pressure pipeline, typically mounted on the right side under the roof of the working area and having a diameter of 1.2 m (with a cross-sectional area of 1.13 m^2), employs a technique to mitigate end oscillations (termed "squelch") and associated flow pulsations. This is achieved by narrowing the ventilation pipeline at the outlet to form a "contraction cone", a practice standard across all forced ventilation pipelines at the Kupol mine. The cross-sectional area at the "nozzle" of this "contraction cone" is between 0.75 and 0.8 m^2, resulting in a contraction degree of 1.4, which improves the stability of the jet flow and extends its effective range.

Experimental Approach and Methodology

Experimental studies were conducted in a dead-end mine working (crossdrift NE 931-250) at the Kupol mine. An industrial mine fan, the Alphair 4200-VAX-2700 VMP, with a rated capacity of 17.9 m^3/s and head of 233.5 daPa, was in operation, supplying ventilation to the pressure pipeline.

Air velocity measurements were taken in a steady-state flow mode, achieved by directing a fresh air jet at a flow rate of 17.4 m^3/s (initial jet velocity of 21.75 m/s) towards the face.

The study evaluated five variations in the distance between the ventilation pipeline's end and the working face. The initial setup included a conventional 10-m setback, followed by a 15-m setback as permitted by safety regulations for workings with a cross-section larger than 16 m^2. Experimental setups included setbacks of 17, 19, and 21 m, with the latter being of particular interest for its practical applicability and acceptance by the Kupol mine management.

To thoroughly examine the flow's spatial structure, the air space at the dead-end face was mapped with a grid of velocity measurement points across various cross-sections. In each selected cross-section, velocities were measured at 25 points (forming a 5 × 5 grid with 0.75 m between points, approximating 1 m near the walls).

Cross-sections for measurement were arranged sequentially from the working face (1, 2, 3, 4... m), including one 1 m from the flight's end towards the working face. Measurements were also conducted at two additional cross-sections, one 1 m from and another 10 m from the flight's end towards the mine's entrance, with the latter cross-section assessing the outflow from the working. Incoming and outgoing airflow rates were compared to verify the data. This comprehensive mapping allowed for a detailed analysis of the flow's spatial dynamics.

Airflow velocities were measured using two APR-2 anemometers, with an error margin of ±(0.2 + 0.05U) m/s, where U denotes the airflow velocity. Distances within the dead-end working were measured using a Leica DISTO D3 laser distance gauge, accurate to ±1.5 mm.

Additional insights and the flow's spatial dynamics were further delineated through three-dimensional mathematical modeling in the ANSYS Fluent software.

Both empirical and numerical simulations identified consistent flow patterns within the dead-end working under forced ventilation and varying pipeline setbacks of 15–21 m (with form factor of $f = L/\sqrt{S}$ = 2.78, 3.14, 3.52, 3.89).

A 10-m setback was also examined for comparison, given its lower form factor (f = 1.85), which is not typically practiced.

Results of field and numerical experiments

When the ventilation duct's end is positioned 15–21 m from the working face, which has a cross-sectional area of 29.2 m^2), injected air jet broadens and generates a substantial primary vortex that encompasses the whole area being ventilated. This observation aligns with well-established concepts derived from previously published research.

The creation of this vortex is a consequence of the mass conservation principle (continuity equation) and is consistent across various implementations of forced ventilation. This has been validated through comprehensive field and computational experiments, which have also uncovered new insights.

Let us outline the key patterns of the vortex flow that emerges when a constricted jet enters a dead-end face.

The core dynamics of the vortex flow initiated by the inflow of a constricted jet to a dead-end face can be summarized as follows: The flow rate of fresh air in the incoming jet (Q_0) equals the flow rate of air exiting the dead-end face ($Q_–$). Therefore, by the law of conservation of mass, the average cross-sectional velocities of the incoming jet (Q_0) and the exiting air ($U_–$) near the working's entrance are proportional to the cross-sectional area of the working (S) relative to the cross-sectional area of the pipeline (s).

It can be deduced that the ratio of the kinetic energy of the incoming flow E_0, as determined by U_0, to the kinetic energy of the outgoing flow $E_–$, as determined by $U_–$, is equivalent to the ratio of the jet velocity at the initial cross-section to the air velocity exiting the dead-end working.

In algebraic terms, the foundational equations of forced ventilation, assuming constant density, are as follows:

$$\frac{U_0}{U_-}=\frac{S}{s}, \quad \frac{E_0}{E_-}=\frac{U_0^2 s}{U_-^2 S}=\frac{U_0}{U_-}=\frac{S}{s}. \qquad (8)$$

From these equations, it's clear that a larger S/s ratio indicates a more powerful jet, capable of expending more energy on vortex formation (including turbulent pulsations) and penetrating the working face. In our case, this ratio is 36.25. For comparison, a traditional working of 4 m² (2 m × 2 m) with a 400-mm pipeline has a smaller ratio of 31.85, similar to a 16 m² working with an 800-mm pipeline.

Figure 1, produced from numerical modeling for the maximum permissible setback in workings larger than16 m² with a 15 m distance from the working face, vividly shows how the jet impinges on the working face and scatters. This effectively aerates the area adjacent to the working face and triggers the return flow. The modeling was performed in ANSYS Fluent software, set to a steady-state with the Realizable k-epsilon turbulence model [21–23].

Since the axis of the ventilation pipeline is conveniently located at the top right (from the perspective of facing the working face), the cross-section of the working, aerodynamically speaking, is divided into two zones. The “concurrent” zone is adjacent to the axis of the ventilation jet in the upper right corner of the working cross-section, conceptually separated by a diagonal from the upper left to the lower right. In this zone, the air drawn by the active jet moves toward the working face. The opposite side is the “return” zone, where air flows away from the working face.

This fundamental large-scale flow pattern is evident in both the field experiment (in Fig. 2, *a*, *b*) and the computational modeling (Fig. 3), outlining the overall structure of air movement at the face.

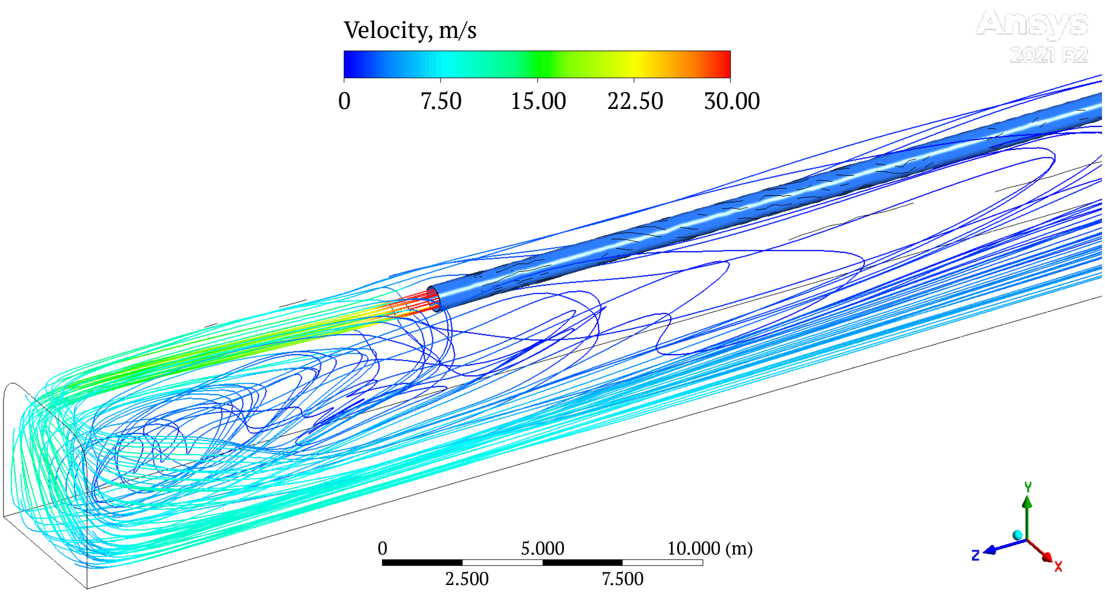

Fig. 1. Illustration of the spatial structure of streamlines with color coding corresponding to the magnitude of the velocity vector during forced ventilation in a dead-end working, showcasing the ventilation duct end setback 15 m from the working face where the jet impacts the working face

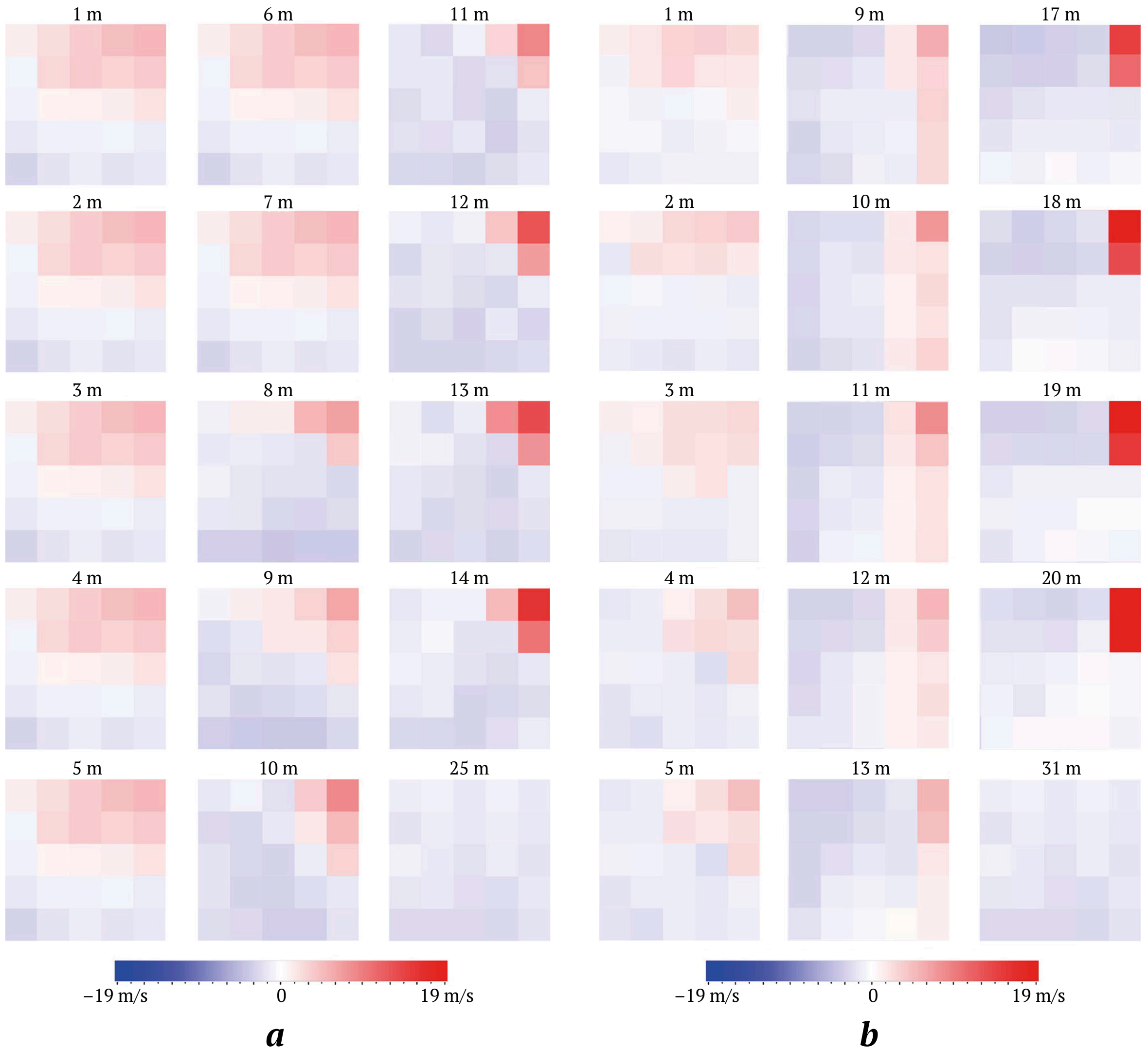

Fig. 2. Airflow velocity measurements at various cross-sections and points with the ventilation duct setback from the working face: *a*) at 15 m (note: 25 m marks the distance of 10 m from the pipeline's end to the working's entrance); *b*) at 21 m (note: 31 m indicates the distance of 10 m from the pipeline's end to the working's entrance)

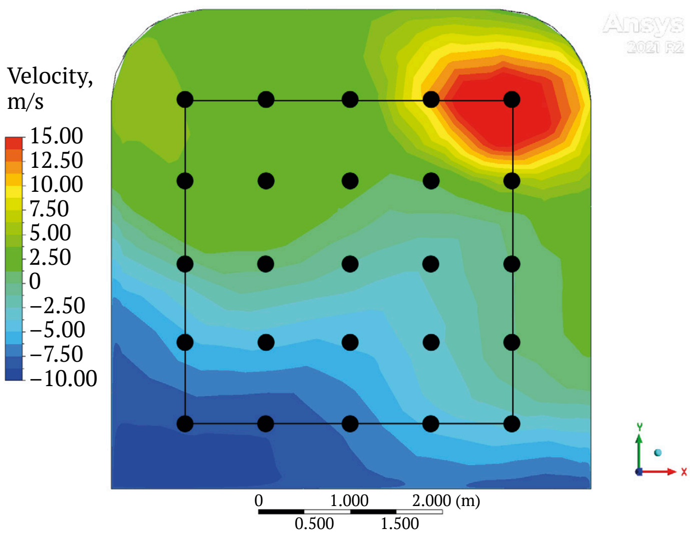

Fig. 3. Calculated air velocity distribution across the working's cross-section (facing the working face) 5 m from the working face with a 10-m setback of the flight's end and the standard "grid" of air velocity measurement points used in the field experiment

In the studied scenario, mass balance is maintained across any cross-section of the dead-end working—the flow rate moving from the working face (either concurrent with or outgoing from the jet flow) is equal to the flow rate moving toward the working face (either concurrent with or fresh flow entering through the pipeline).

Consequently, the flow rate directed to the working face varies from section to section. This variation allows the division of the dead-end working space under normal ventilation by an active jet into five conditionally demarcated zones (starting from the working face):

1. The zone of main flow reversal and "washing" near the working face surface.

2. The zone encompassing the "head" and "body" of the main vortex of the flow structure, extending from the end of the ventilation flight to the point of reversal and initiation of the main return flow from the working face.

3. The zone of the "tail" of the main vortex, which is shaped by the ejection (suction) of air not only from the side of the jet but also due to the constriction from behind the jet around the end of the ventilation pipeline.

4. The zone of flow "return" within the "tail" of the main vortex, resulting in an asymmetric distribution of flow velocities.

5. The classical flow zone, where the entire cross-section of the working is filled with the outgoing flow, and the velocity is purely axial (along the working's length axis), excluding turbulent pulsations.

A schematic of this 5-zone structure is illustrated in Fig. 4.

In the first zone, the "longitudinal (axial) air flow rate" is nearly zero; it substantially exceeds the supplied ventilation air flow rate in the second and third zones and matches the supplied ventilation air flow rate in the fourth and fifth zones.

We highlight that this 5-zone structure along the length of the working effectively describes the jet's active influence on ventilation when it extends to the working face. Should the jet lack sufficient energy and momentum to reach the working face, a sixth zone emerges. This is not a single vortex but a cascade of progressively weaker vortices, often leading to the development of a "stagnant" zone.

In our comprehensive field and computational studies with a maximum setback of 21 m (corresponding to a form factor of 3.75), a stagnant zone did not form. Under the conditions described (working cross-section and fresh air flow rate), a 21-m setback ensured a vigorous jet "flow" towards the working face.

Figure 5 illustrates the distributions of the concurrent (from the working face) air flow rate Q along the entire length of the working, normalized to air flow rate Q_0 at the ventilation pipeline outlet. The concurrent air flow was determined by integrating the axial component of the air velocity in the working across the portion of the cross-section where the airflow is directed from the face towards the mine's opening.

In all three modeled scenarios, a single vortex with a complex three-dimensional structure was present in the portion of the working closest to the face. Due to this asymmetry, a local maximum in the concurrent airflow was detected near the face (within a 3–4 m range) as depicted in Fig. 5.

Near the working face in zone 1, there are generally three possible airflow behaviors: the jet can "bump" against the working face, the incoming air can "wash" over the face, or a separate low-intensity vortex can form, creating a stagnant zone and effectively "isolating" the working face from the active jet. It is important to note that this last scenario was not observed in our field and computational experiments for setback distances up to 21 m.

The longitudinal airflow velocities directed towards the working face, measured 1 m from it, are typically found to be within 10–20% of the initial velocity of the jet entering the working. This is adequate for efficient ventilation of the space near the face and prevents the formation of stagnant zones.

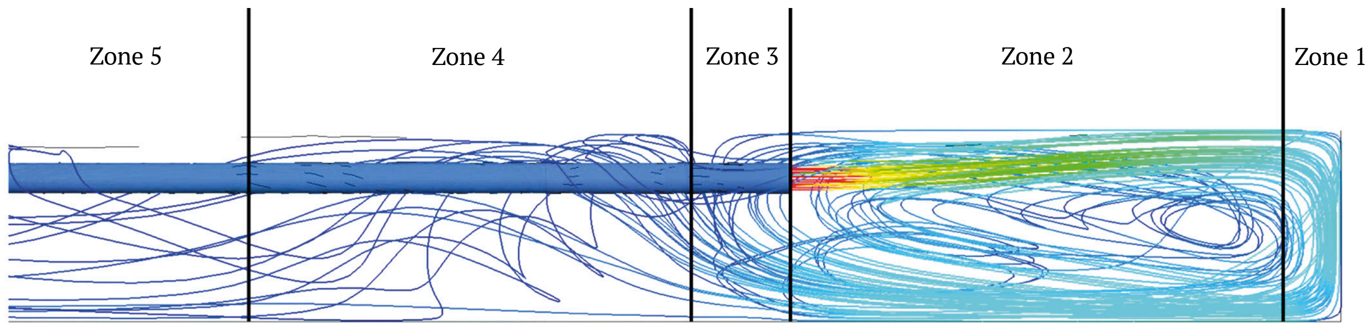

Fig. 4. Schematic illustration of the 5-zone structure of ventilation at the dead-end face

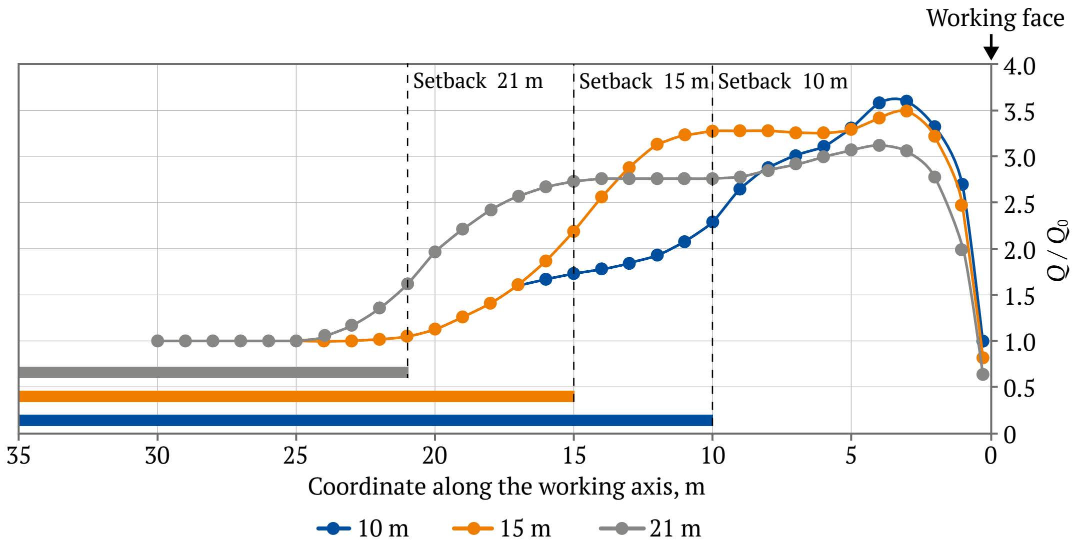

Fig. 5. Relationships of concurrent airflow along the working axis for various setback distances of the ventilation duct's end (vertical dashed lines indicate the positions of the ventilation duct's end for enhanced clarity)

Moreover, these velocity values tend to decrease as the setback distance of the pipeline from the working face increases, or, given the constant cross-sectional conditions of the described experiment, as the form factor increases (Fig. 6).

For the conditions of the mentioned experiment, the jet has not yet reached its limit of forward movement with a 21 m setback from a 29.2 m^2 working (form factor of 3.75) and a fresh air supply rate of 17.4 m/s. However, with further increases in the setback (and a form factor of about 6), the jet's range reaches its limit.

The trend line in Figure 6, determined by the least squares method, corresponds to the following formula:

$$\frac{U_{max}(L-1)}{U_0} = 0.388 - 0.065\frac{L}{\sqrt{S}}. \qquad (9)$$

The numerical experiment's results demonstrate a comparable pattern. For the maximum longitudinal velocity at a distance of 1 m from the working face, the equation is:

$$\frac{U_{max}(L-1)}{U_0} = 0.554 - 0.083\frac{L}{\sqrt{S}}. \qquad (10)$$

The numerically calculated relationship for the concurrent air flow rate relative to parameter $L/\sqrt{S}$ one meter from the face is:

$$\frac{Q\ (L-1)}{Q_0} = 0.195 - 0.02\frac{L}{\sqrt{S}}. \qquad (11)$$

The values from equations (9) and (10) are approximately proportional, but the numerically calculated maximum air velocities at a cross-section 1 m from the face are about 1.7–1.8 times greater. This discrepancy may be due to at least two factors:

1. The model's failure to account for potential non-stationary, random factors such as oscillations at the end of the ventilation pipeline.

2. The imprecision in capturing measurement points within the local zone of the working cross-section where maximum flow velocity occurs.

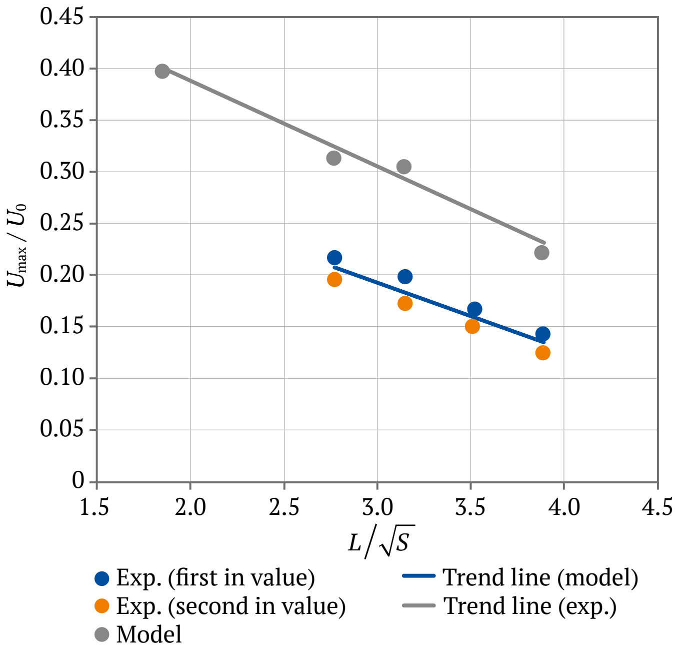

Fig. 6. Relationship between the maximum longitudinal velocity (relative to the jet's initial velocity) at the working face and the form factor; comparative analysis of modeling and experimental data: highlighting the two highest velocities at measurement points 1 m from the working face

It is crucial, however, that the velocity field in numerical modeling is not lower than that in the experiment, which allows us to use the experimental data as a conservative estimate for evaluating the efficiency of working ventilation.

Formulas (9)–(11) indicate that, within $L < 6\sqrt{S}$, the jet's range is ample for effective face ventilation ($100\% U_{max}/U > 1.15\%$). This reinforces the accuracy of formulas (1)–(3).

Consequently, the field experiment's findings indicate that as the distance from the pipeline's end increases, there's a corresponding decrease in air exchange intensity. This pattern suggests the feasibility of significantly extending the setback of the ventilation duct's end from the working face, provided the form factor remains below 6.

Conclusion

The comprehensive field experiment aimed at analyzing the flow structure (specifically, air velocity) within a dead-end working utilizing forced ventilation was conducted across five different ventilation pipeline setback distances. These distances ranged from 10, 15, 17, 19, to 21 m for a pipeline with a diameter of 1200 mm. The cross-section of the working averaged 29.2 m^2, with a fresh air supply rate of 17.4 m^3/s, and the initial cross-sectional area of the jet ranged from 0.75 to 0.8 m^2. This setup ensured an initial jet velocity of 21.75 to 23.8 m/s, conducive to effective, long-range ventilation.

In all scenarios where the ventilation pipeline setback behind the working face (10 to 21 m), the ventilation jet effectively reached the working face of the dead-end working, washed over it, turned around, and proceeded towards the entrance of the dead-end working. This process generated multiple turbulent vortices of varying sizes within the near-face ventilated zone, actively mixing the air flow.

The result was an air mixture near the face that was nearly homogeneous, displaced by the incoming fresh jet, and evacuated from the working space by the outgoing flow. Importantly, no stagnant zones were formed, which could potentially retain air contaminated with flue gases and dust. Such stagnant zones were not detected in the field experiment.

The data from computer simulations of the three-dimensional turbulent flow in the ANSYS software provided corroboration for the patterns observed in the field experiment. In all cases examined, the outgoing air flow within the working stabilized at a distance of 10 m from the end of the ventilation pipeline and remained constant up to the working face.

The findings of this study support the practicality of increasing the setback of the ventilation pipeline to up to 20 m from the working face in dead-end mine workings with a cross-section larger than 20 m^2, particularly when the air velocity at the outlet of the ventilation pipeline is around 20 m/sec.

The findings from this investigation underpin the safety rationale for a hazardous production facility that has been developed and successfully applied in practice. This implementation has ensured high productivity and a consistent level of safety for underground mining operations at the Kupol gold-silver mine.

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Information about the authors

Anton A. Kamenskikh – Cand. Sci. (Eng.), Researcher at the Department of Aerology and Thermophysics, Chief Researcher of the Department of Aerology and Thermophysics, Mining Institute of the Ural Branch of the Russian Academy of Sciences, Perm, Russian Federation; ORCID 0000-0002-6456-5487; e-mail timir2418@gmail.com

Grigoriy Z. Faynburg – Dr. Sci. (Eng.), Professor, Chief Researcher of the Department of Aerology and Thermophysics, Mining Institute of the Ural Branch of the Russian Academy of Sciences, Perm, Russian Federation; ORCID 0000-0002-9599-7581, Scopus ID 57217891724; e-mail faynburg@mail.ru

Mikhail A. Semin – Dr. Sci. (Eng.), Scientific Secretary, Mining Institute of the Ural Branch of the Russian Academy of Sciences, Perm, Russian Federation; ORCID 0000-0001-5200-7931, Scopus ID 56462570900, ResearcherID S-8980-2016; e-mail seminma@inbox.ru

Aleksey V. Tatsiy – Engineer, Mining Institute of the Ural Branch of the Russian Academy of Sciences, Perm, Russian Federation; ORCID 0009-0001-2514-6204; e-mail alexeytaciy@gmail.com

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