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ANALYSIS AND EVALUATION OF THE POTENTIAL OF NATURAL DRAFT VENTILATION IN DUAL-PURPOSE STRUCTURES

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Abstract. The accident rate in underground facilities used as dual-purpose structures requires special attention to maintaining a safe atmosphere, particularly under power outage conditions. These confined underground spaces, lacking the ability for rapid forced air renewal, demand efficient and autonomous life-support solutions. The study assesses the potential of using natural draft ventilation in underground structures to enhance their reliability and safety.

The research includes an analysis of the current state of ventilation systems in Ukraine's mining industry, which reveals that a successful progress has been achieved in optimizing the performance of main ventilation fans and sealing internal air leaks. However, significant problems, such as delays in replacing obsolete fan motors and repairing external structures, still remain. The reduction in the length of the ventilation network also indicates potential gas leakage risks. These factors highlight the need for sustainable, energy-independent ventilation methods.

The research methodology is based on analytical calculations derived from physical laws describing the interaction of air masses. Parameters such as pressure and gas density differences, temperature gradients, mine depth, and aerodynamic resistance were considered. The calculations were performed using a decommissioned mine as a representative example of a potential dual-purpose structure. Depression survey data were used to determine temperature conditions in intake and exhaust shafts, as well as parameters of natural draft flow.

The scope of the study covers the design and operation of underground dual-purpose structures. The practical significance lies in improving their autonomy and safety during emergencies, particularly under power outage conditions.

The study's conclusions confirm the high potential of natural draft for ventilating confined underground systems. However, several hazardous factors were identified, including unpredictable changes in flow direction and velocity, the risk of airway blockage, and the potential for spontaneous combustion. The implementation of continuous air environment monitoring systems, flow control devices, early hazard detection systems, and comprehensive personnel training programs is recommended to minimize risks and ensure reliable operation.

Keywords: dual-purpose structures, natural draft, ventilation, mine, safety.

1. Introduction

The use of decommissioned mines as dual-purpose structures requires further clarification, since in typical contexts this term is often associated with urban structures such as subways or parking lots, which are easily accessible to the general public in densely populated areas. However, in the case of coal mines in Ukraine, especially under wartime conditions, their particularity lies in depth of their location (300–1000 m or more) and their natural resistance to missile and air attacks. These mines are not intended for rapid mass sheltering but for creating highly protected, autonomous facilities for critical functions: backup command centers, defense production sites, medical units, or evacuation hubs for personnel during prolonged power outages. Thus, mines serve not as a replacement but as a complement to the traditional civil protection system, providing resilience for regions with dispersed populations and industries.

In this context, the issue of safety and life support in underground structures that can serve as shelters becomes especially relevant. Ensuring effective air exchange in confined spaces with limited access to energy systems and the risk of power failure of forced ventilation units presents a major engineering challenge. Although the current state of ventilation infrastructure in active Ukrainian mines shows efforts toward modernization and implementation of energy-efficient technologies (notably in

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electricity savings [1]), the presence of outdated equipment, unresolved problems with workings sealing, and excessive reduction of ventilation networks [2–4] indicate an overall instability of forced ventilation systems. In such critical conditions, alternative ventilation mechanisms, particularly natural draft, cease to be merely auxiliary and become essential for maintaining vital environmental parameters [5–7].

Consequently, the concept of using natural draft as the basis for ventilation in underground dual-purpose structures is gaining importance. Unlike mechanical systems, natural draft is based on physical principles of air density and pressure differences caused by temperature gradients. The effectiveness of this mechanism largely depends on the facility's configuration, depth, presence of vertical shafts, and daily or seasonal temperature fluctuations. At the same time, obstacles such as irrational structural decisions or breaches of sealing can reduce the aerodynamic efficiency of the system, requiring careful engineering analysis when repurposing old mines.

However, transitioning a mine to natural draft ventilation is not a standard operation; it is rather an exceptional mode, equivalent to an emergency condition, and subject to strict limitations and control. According to the current "Safety Rules for Mining Operations" [7] and the requirements of KD 12.01.03-2002 [8], long-term shutdown of main ventilation fans (MVF) is permitted only under a special Project that must include detailed gas emission calculations, an assessment of natural depression, as well as confirmation of the minimum air flow rate through measurements. Particular attention should be paid to the creation of an initial ventilation impulse: in operating mines, spontaneous airflow formation after MVF shutdown is not guaranteed, which can lead to methane accumulation. Therefore, any long-term ventilation without forced airflow requires prior analysis, approval by the State Labor Service, and amendments to the Emergency Response Plan, emphasizing the need to find reliable methods for draft stimulation.

Considering these aspects, this paper focuses on analyzing the potential of natural ventilation mechanisms as the foundation for a reliable, energy-independent life-support system in Dual-Purpose Structures. The research object is a decommissioned mine adapted to new functional requirements. Using it as an example, the study evaluates the efficiency of natural air exchange, identifies key factors influencing its effectiveness, and formulates recommendations for designing a safe environment under potential energy isolation conditions. The results contribute to a deeper understanding of natural ventilation processes and can serve as a foundation for developing energy-efficient approaches to underground ventilation in critical scenarios.

2. Methods

The study is based on analytical calculations of the aerodynamic processes involved in the natural ventilation of underground structures. The choice of this methodology is justified by its efficiency and cost-effectiveness, as it allows for quantitative evaluation of air exchange under potential power outage conditions, when mechanical ventilation systems are non-operational. The calculations are grounded in fundamental aerodynamic laws describing the movement of air masses within a branched mine network. The key factors considered in the formation of natural draft include air density differences and the aerodynamic resistance of mine workings. The calculations were performed using standard engineering methods applied in the design of ventilation systems for mining enterprises.

3. Theoretical and experimental parts

Calculation of natural draft and determination of air flow rate.

To assess the possibility of natural ventilation of the mining environment in the event of accidents at underground facilities, let us consider a specific example of the decommissioned Nova mine, which may serve as a dual-purpose facility.

Brief information about the Nova mine. The mine was in the process of decommissioning and belonged to Category I in terms of relative methane content. The total length of mine workings is 3.5 km. The mine ventilation system is of a central type, operating on suction using a ventilation unit equipped with two VOD-21 fans located near shafts No. 8 "bis" (see Fig. 1). Fresh air enters through the cage shaft No. 8 to the 515 m horizon, and then continues through the inclined shaft No. 3 to the 715 m horizon. The exhaust air moves through the inclined shaft No. 1 into the skip shaft No. 8-bis and is released to the surface. According to depression survey data, the volume of air entering the mine is 39.0 m³/s.

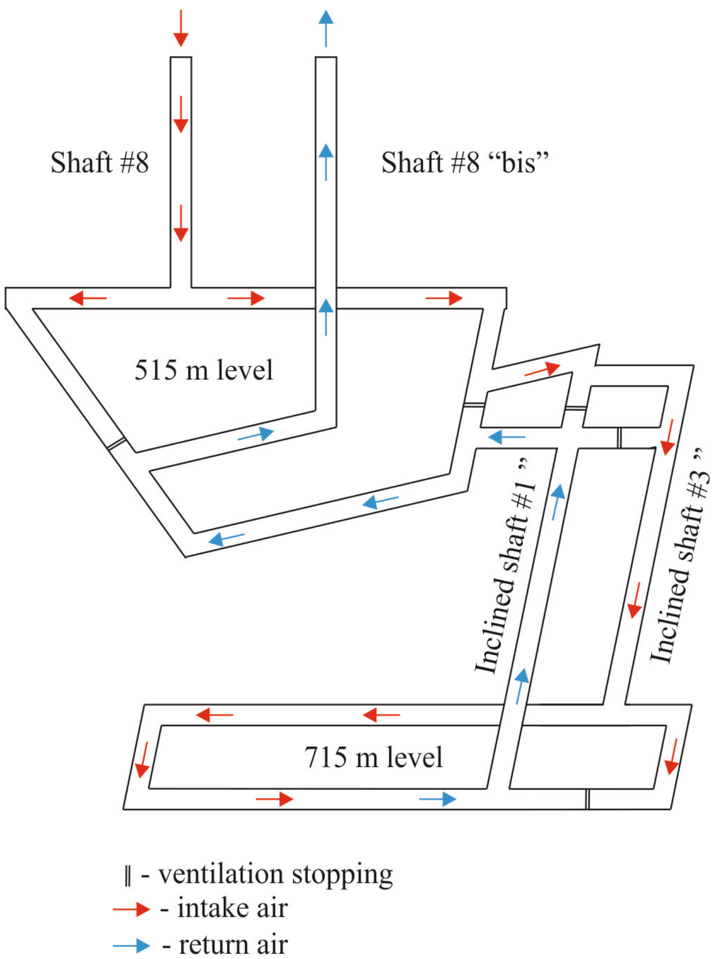

Figure 1 – Mine ventilation scheme

Calculation of air temperature in the ventilation shaft. The air temperature at the mouth of the cage shaft No. 8 during the cold season, t2 (taking into account preheated intake air), is assumed to be 2°C. The air temperature at the lower part of the intake shaft, t2, is determined using the formula [8]:

$$t_2 = f\left(-19.6 + \sqrt{178 + A + B + \frac{H_i}{3.42}}\right) \text{ °C}, \quad (1)$$

where A and B – constants for each month; H_i – depth of the intake air shaft, m; f – coefficient accounting for shaft inclination (for a vertical shaft, $f = 1$).

At the Nova mine, fresh air first moves through the vertical shaft No. 8 and then through the inclined shaft No. 3. The vertical height of the shaft No. 8 is 515 m. The vertical height of the inclined shaft No. 3, with a length of 262 m, is 200 m. Therefore, the total length of the ventilation air path through the shafts is 715 m.

It is known that the longer the air stream travels through mine workings, the more it heats up. Consequently, the air temperature at the lower part of the inclined shaft will be significantly higher compared to that of a vertical shaft at the same elevation. According to the results of the depression survey made in 2019, the temperature at the lowest point of the vertical shaft No. 8 is 18 °C, while the temperature at the highest point of the inclined shaft No. 3 is 18.6 °C. Therefore, the temperature increase factor is 1.033 (f = 1.033).

It is assumed that the mine will be ventilated by natural draft for five months (from October 1 to March 31). During this period, the minimum thermal depression occurs in October and March, while the maximum value is reached in January.

For the 715 m horizon, according to formula (1), the calculated air temperature values are:

- for October and March: t_2 = 9.9 °C;
- for January: t_2 = 5.9 °C.

The average air temperature in the intake shaft, tr °C, is determined using the formula [8]:

$$t_r = \frac{\Delta H_i \cdot t_0 + 0.5 \cdot (t_1 - t_2) \cdot H_i}{H_i + \Delta H_i} \text{ °C}, \quad (2)$$

where ΔH_i – difference in elevation marks between the shaft collars, m; t_0 – average monthly air temperature at the earth surface, °C.

Considering that for the Nova mine $\Delta H_i = 0$, according to formula (2) we obtain:

- for October and March – 6.0 °C;
- for January – 4.0 °C.

Calculation of air temperature in shafts for the cold season.

The air temperature (°C) at the lower part of the ventilation inclined shaft No. 1 is determined by the following formula:

$$t_3 = 11.1 + 0.212 \cdot t_r \text{ °C}, \quad (3)$$

where t_r – natural air temperature at the lowest point of the inclined ventilation shaft No. 1, °C, determined by

$$t_r = t_e + \frac{H_v}{G} \text{ °C}, \quad (4)$$

where t_e – average annual air temperature at the earth surface, °C; H_v – depth of the lowest point of the inclined ventilation shaft No. 1, m; G – geothermal gradient in the area of the Nova mine, m/°C.

Formula (3) takes into account the air leakage from the intake shaft into the ventilation shaft. Assuming from Table 1 [8] that t_e = 8.2 °C, and given that the average geothermal gradient for this area of Donbas is G = 33 m/°C [9], according to formula (4) we obtain: t_r = 29.9 °C, and by applying formula (3) we get: t_3= 17.44 °C.

As the air moves upward through the ventilation shafts (the inclined shaft No. 1 and the skip shaft), its temperature changes; at the mouth of the skip shaft, the temperature equals

$$t_v = \frac{\Delta H_v \cdot t_0 + \left[t_3 - 0.5 \cdot \theta_x \cdot (H_v + \Delta H_v)\right] \cdot H_v}{H_v + \Delta H_v} \text{ °C}, \quad (5)$$

where θ_x=0.006 m/°C – temperature gradient in the ventilation shafts; ΔH_v = 0 m – difference in elevation marks between the shaft collars (in the case of multiple ventilation shafts).

Considering these data, formula (5) takes the following form

$$t_4 = t_3 - 0.5 \cdot \theta_x \cdot H_v = 17.44 - 0.5 \cdot 0.006 \cdot 715 = 15.3 \text{ °C}.$$

The average air temperature in the ventilation shafts is then determined as

$$t_v = 0{,}5 \cdot (t_3 + t_4) = 0{,}5 \cdot (17.44 + 15.3) \approx 16.4 \text{ °C}.$$

Calculation of natural draft.

The value of natural draft (daPa) is determined using the formula

$$h_e = 0.0047 \cdot H_m \left(t_v - t_r\right) \text{ °C}, \quad (6)$$

where H_m – effective mine depth, m.

The calculated natural draft values are as follows:

- for November and march:

$$h_e = 0.0047 \cdot 715 \cdot (16.4 - 6) = 34.95 \text{ daPA (mm Hg)},$$

- for January

$$h_e = 0.0047 \cdot 715 \cdot (16.4 - 4) = 41.67 \text{ daPA (mm Hg)},$$

Thus, according to the calculations, the natural draft value ranges from 34.95 daPa to 41.67 daPa.

Determination of airflow rate for mine ventilation.

The airflow rate for mine ventilation is calculated according to the "Guidelines for the Design of Coal Mine Ventilation Systems" [10] using the formula

$$Q_m = 1{,}1 \cdot \left(\sum Q_1 + \sum Q_2 + \sum Q_3\right) = 1.1 \cdot (474 + 270 + 84) = 911 \text{ m}^3\text{/min}, \quad (7)$$

where 1.1 – coefficient accounting for uneven air distribution in the mine network; ΣQ_1= 474 m³/min – air consumption for localized ventilation of maintained workings (based on depression survey data); ΣQ_2 = 270 m³/min – air consumption for localized ventilation of chambers; ΣQ_3 = 84 m³/min – air leakage through ventilation structures (according to depression survey results).

The air flow rate for mine ventilation must meet the following conditions:

$$Q_m \geq \frac{110}{C\text{-}C_0} \sum I_u \quad \text{m}^3\text{/min}, \quad (8)$$

where C – permissible gas concentration in exhaust air streams, 0.75%; C_0 – gas concentration in atmospheric air at the surface, assumed to be 0 for methane emission calculations [10]; $\Sigma \overline{I_u}$– average absolute gas emission in exhaust ventilation streams (according to depression survey results, 0 m³/min).

$$Q_m = 0 \text{ m}^3\text{/min}.$$

Determination of air volume entering the mine due to natural draft. Calculation of mine network resistance.

Airflow in mine workings is determined by the magnitude of natural draft and the aerodynamic resistance of the mine workings. The total mine resistance was obtained from the depression survey of 2019.

The total aerodynamic resistance of the mine is determined using the formula [10]

$$R_m = \frac{h_m + h_{em}}{Q_m^2} = \frac{58 + 4.07}{39^2} = 0.041 \text{ k}\mu.$$

where h_m = 58 mm Hg – total mine depression; h_{em} = 4.07 mm Hg – natural draft depression at the time of the survey; Q_m = 39 m³/s – airflow rate in the mine.

Determination of air quantity by calculation. The air quantity entering the mine under the influence of natural draft is determined using the formula [3, 4]

$$Q_{max}=60\sqrt{\frac{h_e}{R_m}} \ \text{m}^3/\text{min},$$

- for November and March – 1750 m³/min;
- for January – 1912 m³/min.

To quantitatively determine the dependence of airflow rate on key operational parameters, a regression analysis was conducted. The goal was to create statistically significant linear models describing the dynamics of airflow rate during different periods of the year.

The analysis of airflow rate (Q_{max1}) for November – March was performed using a simple linear regression model, where the only independent variable was t_1.

The model demonstrates exceptionally high quality: the coefficient of determination (R-squared) is 0.97. This indicates that 97.17% of the variability in air flow rate is explained by the change in parameter t_1. The statistical significance of the model is confirmed by the Significance F value (approximately $1.77 \cdot 10^{-07}$), which is much lower than α=0.05 level. Based on the calculated coefficients, the regression equation takes the following form

$$Q_{max1} = 1607.33 - 43.21 \cdot t_1, \ \text{m}^3/\text{min}.$$

The inverse relationship (coefficient – 43.21) indicates that an increase in t_1 leads to a significant decrease in air flow rate.

Conversely, for January, the airflow (Q_{max2}) was modeled using a multiple linear regression with two independent variables: H_i and t_1. The coefficient of determination (R-squareв) is 0.761, meaning that 76.19% of the variability is explained by the combined effect of these factors. The overall significance of the model is confirmed by the analysis of variance (Significance F: 0.0066). Independent predictors, H_i and t_1, are statistically significant at the α = 0.05 level.

The regression equation for January is

$$Q_{max2}= 1254.50 + 0.38 \cdot H_i - 13.69 \cdot t_1, \ \text{m}^3/\text{min}.$$

The variable t_1 maintains an inverse relationship, though weaker than in the Q_{max1} model (coefficient –13.69). Meanwhile, Hi shows a positive relationship (coefficient +0.38), indicating its direct contribution to the overall airflow rate.

Thus, the conducted regression analysis made it possible to quantitatively determine the influence of key parameters and revealed significant seasonal differences in the mechanisms of air consumption formation. The Q_{max1} model is highly deterministic and reliable for forecasting, whereas the Q_{max2} model, though statistically significant, confirms a multifactorial dependency.

4. Results and discussion

In the course of the study, using the example of the decommissioned Nova mine, analytical calculations were carried out, confirming the practical feasibility of using natural ventilation as a backup or primary life-support mechanism for dual-purpose underground structures in the absence of power supply. Calculations for the cold season (November–March) showed that the temperature difference ensures a natural depression within the range of 34.95–41.67 daPa, and the airflow volume (1750–1912 m³/min) almost doubles the calculated rate of 911 m³/min. This finding represents scientific novelty, as it is the first time that the possibility of maintaining normative air exchange without forced ventilation has been confirmed for a real decommissioned mine. This result provides a foundation for rethinking the role of natural ventilation in the safety systems of underground facilities.

The practical value of these results lies in the potential to design energy-independent ventilation systems for underground shelters and emergency facilities – an aspect critically important for civil defense and under wartime conditions.

Natural draft provides a substantial air exchange reserve, allowing for responses to increased methane emissions, temporary blockages of mine workings, or localized fires. However, certain limitations and risks must be considered: the efficiency of natural ventilation depends on weather conditions, shaft configuration, and structural tightness. There are also potential risks of unpredictable airflow reversals, blockages, and spontaneous combustion, which necessitate the implementation of monitoring, control, and regulation systems to ensure safety.

5. Conclusion

The study and numerical calculations based on the example of the decommissioned Nova mine confirm the potential feasibility of effective ventilation for dual-purpose underground structures through natural draft, especially during the cold season.

1. Efficiency of natural draft: The calculations showed that natural draft values during the cold period (November–March) range from 34.95 daPa to 41.67 daPa, which is sufficient to ensure significant air exchange.

2. Ensuring the required airflow rate: The calculated airflow entering the mine due to natural draft ranges from 1750 m³/min to 1912 m³/min, which significantly exceeds the required airflow rate for ventilating the mine chambers and workings (911 m³/min). This indicates the high efficiency of natural air exchange under the considered conditions.

3. The regression analysis confirmed the existence of stable dependencies between airflow rate and key thermodynamic parameters. In November and March, airflow is primarily determined by ambient air temperature, while in January, it is influenced by both temperature and shaft depth. The resulting equations describe general

trends in natural draft variation and can be used for preliminary engineering calculations in mine ventilation systems.

4. Critical importance for dual-purpose structures: The ability to rely on natural ventilation is extremely valuable for dual-purpose underground structures, especially in scenarios involving power outages or damage to mechanical systems, as it ensures the essential air exchange required for survival.

5. Importance of risk management: Despite its advantages, natural draft is associated with significant hazards, including unpredictable changes in flow direction and velocity, possible channel blockages, and spontaneous combustion risks.

6. Need for an integrated approach: For safe and effective use of natural draft, comprehensive design, continuous monitoring of air parameters and additional safety measures are required, including early hazard detection systems and staff training.

These conclusions emphasize the relevance of further research and the development of technical solutions for integrating natural ventilation systems into the operation of dual-purpose underground structures, ensuring their reliability and safety under emergency conditions.

Conflict of interest

Authors state no conflict of interest.

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АНАЛІЗ ТА ОЦІНКА МОЖЛИВОСТЕЙ ПРОВІТРЮВАННЯ СПОРУД ПОДВІЙНОГО ПРИЗНАЧЕННЯ ПРИРОДНОЮ ТЯГОЮ

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Анотація. Аварійність у підземних спорудах, що використовуються як об'єкти подвійного призначення, вимагає особливої уваги до забезпечення безпечної атмосфери, особливо за умови знеструмлення. Ці обмежені підземні простори без можливості швидкого примусового підсвіження повітря потребують ефективних, автономних рішень для життєзабезпечення. Дослідження оцінює можливості провітрювання підземних споруд шляхом природної тяги для підвищення їх надійності та безпеки.

Робота включає аналіз поточного стану вентиляційних систем у гірничій промисловості України. Встановлено успішне виконання планів з оптимізації роботи вентиляторів головного провітрювання та герметизації внутрішніх витоків. Виявлено, що значні проблеми є з невиконанням заміни застарілих двигунів вентиляторів головного провітрювання та ремонту зовнішніх споруд. Скорочення протяжності вентиляційної мережі, також вказує на ризики витоків газу. Ці аспекти підкреслюють потребу в стійких, енергонезалежних методах провітрювання.

Методологія дослідження базується на аналітичних розрахунках фізичних законів, що описують взаємодію повітряних мас. Враховано різницю тисків і густини газів, температурний градієнт, глибину шахти та її аеродинамічний опір. Розрахунки виконано на прикладі ліквідованої шахти, що є репрезентативним об'єктом для потенційного подвійного призначення. Використані вихідні дані депресійної зйомки для розрахунку температурного режиму у повітроподавальних та вентиляційних стволах, а також параметрів природної тяги.

Область застосування результатів охоплює проектування та експлуатацію підземних споруд подвійного призначення. Практичне значення полягає у підвищенні їх автономності та безпеки за умов надзвичайних ситуацій, зокрема при знеструмленні.

Висновки роботи підтверджують високий потенціал природної тяги для провітрювання замкнутого контуру підземних об'єктів. Проте, ідентифіковані й небезпечні фактори: непередбачувані зміни напрямку і швидкості потоку, ризик закорковування каналів, сприяння самозайманню. Рекомендується впровадження систем постійного моніторингу повітряного середовища, пристроїв для контролю потоку, систем раннього виявлення небезпек та комплексних програм навчання персоналу для мінімізації ризиків та забезпечення надійної експлуатації.

Ключові слова: споруди подвійного призначення, природна тяга, вентиляція, шахта,безпека**.**