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Mitigation of air leakage in underground coal mines: A case study of the Quang Ninh coalfield, Vietnam

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Abstract. The stability and efficiency of ventilation systems in underground coal mines are crucial for ensuring production safety and protecting workers' health. Air leakage not only reduces the efficiency of fresh air supply to working places, including longwall faces, dead-end roadways, and large underground openings, but also contributes to hazards such as spontaneous coal combustion and methane accumulation, which may lead to explosions. In addition, air leakage significantly increases the energy consumption of main fan operation. Therefore, it is necessary to investigate and propose solutions to reduce air leakage in underground coal mines. Based on the mining and ventilation layout, as well as the existing ventilation works, the authors carried out field surveys, measurements, analyses, and evaluations in order to propose measures for reducing air leakage through mine ventilation works. In addition, several design solutions for ventilation gates, ventilation doors, and retaining walls were proposed for application in underground coal mines of the Quang Ninh coalfield, Vietnam. The research methods used in this study included data collection, field surveys, in-situ measurements, field analysis, and evaluation of the obtained results. The proposed solutions have been applied in mine production and have shown positive results, including reduced air leakage, improved ventilation efficiency, better operating performance of the main fans, and lower ventilation costs for the entire mine. The results of this study can also serve as a basis for underground coal mines to develop ventilation plans and to select and install appropriate ventilation works for reducing air leakage throughout the mine.

Keywords: *air leakage, air leakage reduction, ventilation works, main fan stations, underground coal mines, Quang Ninh coalfield.*

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1. Introduction

Underground coal mines operated by Vietnam National Coal-Mineral Industries Holding Corporation Limited are currently facing a number of ventilation-related challenges. Mining activities are being conducted at increasing depths, many mines are classified as grade III or supergrade in terms of gas emission, and ventilation systems are becoming more complex, especially in mines where several levels are mined simultaneously. Under such conditions, significant air leakage through ventilation structures often occurs, resulting in an insufficient air supply to working places [1].

Air leakage refers to the transfer of air from intake airways to return airways without passing through the required working places, such as mining faces, development headings, or large underground openings. It can be classified into internal and external leakage. Internal leakage occurs within mining districts and ventilation structures inside the mine, whereas external leakage mainly occurs through fan drifts and main fan installations. In practice, leakage through ventilation structures may account for 70-90% of the total internal air leakage in a mine. Excessive leakage reduces the amount of air delivered to active workings, worsens underground microclimatic conditions, and negatively affects both labour productivity and workers' health. In mines with high methane emissions, insufficient air quantity may also prevent methane dilution to permissible limits, thereby increasing the risk of fires and explosions [2].

Many studies have addressed the issue of air leakage in underground mines. Previous research has focused on gas control, mine climate, and ventilation processes [3-5]; the characteristics, mechanisms, and intensity of air leakage [6-8]; airflow simulation and the influence of leakage on mine ventilation networks [9-15]; and the regularities of air leakage in underground coal mines [16-18]. Other studies have considered optimization of ventilation networks to reduce leakage losses [19-23], the influence of leakage on spontaneous combustion hazards and fire prevention measures [24-27], as well as air leakage in complex coal mines, mine microclimate assessment, and energy-saving solutions for ventilation systems [28-30]. In the Quang Ninh coalfield of Vietnam, a number of studies have also investigated leakage resistance and leakage assessment in mines [31, 32], ventilation network evaluation and ventilation door systems at Khe Cham Coal Mine [33-35], and the operating conditions of main fan stations at several mines, including Nam Mau Coal Mine [36-39].

Although these studies have made an important contribution to understanding and controlling air leakage in underground coal mines, they have generally focused on individual mines, specific ventilation installations, or individual aspects of ventilation performance. A systematic and large-scale survey of ventilation structures in underground coal mines of the Quang Ninh coalfield has not yet been carried out. In practice, many mines attempt to compensate for leakage by increasing the total air quantity supplied underground. However, this approach increases electricity consumption, accelerates ventilation equipment wear, and may destabilize the ventilation network without eliminating the root causes of leakage. Therefore, a comprehensive study aimed at identifying and proposing effective measures to mitigate air leakage through ventilation structures in underground coal mines of the Quang Ninh coalfield is both necessary and timely. The results of this study can serve as a practical basis for improving ventilation efficiency and enhancing mine ventilation safety in the region.

2. Materials and methods

2.1. Ventilation works in underground coal mines

Ventilation doors are among the most important ventilation works used for regulating and directing airflow in underground coal mines. Due to the dense network of tunnels, underground coal mines often use hundreds of ventilation doors installed at different locations. These doors are concentrated in crosscuts, transport tunnels, and areas adjacent to ventilation shafts. Their main role is to separate airflow, prevent bypassing between fresh and dirty air flows, regulate and distribute airflow to longwall faces and preparatory faces according to the ventilation design, and facilitate transportation by allowing people, equipment, and electric trains to pass through while ensuring the isolation of the ventilation system.

Ventilation doors include automatic ventilation doors, reversing ventilation doors, and manual ventilation doors. Automatic ventilation doors are widely deployed in modern mines such as Ha Lam, Khe Cham, and Vang Danh. These doors use hydraulic or pneumatic piston systems, allowing electric trains to pass through without stopping for manual opening. Reversing ventilation doors are designed with two-way hinges to ensure stable operation when the main fan system reverses the airflow in the event of a malfunction. Manual ventilation doors are still used in preparatory furnace areas and in medium- and small-scale mines.

The materials commonly used for manufacturing ventilation doors are steel or wood covered with corrugated iron. Some modern mines are gradually switching to composite plastic or high-strength steel doors in order to prevent corrosion in humid environments.

A ventilation gate is a ventilation work constructed in mine tunnels to separate fresh air from dirty air. It is installed in mine workings that must remain airtight but are also frequently used by personnel and transport vehicles. To effectively isolate air flows and minimize air leakage, at least two ventilation gates should be installed simultaneously in order to create an air chamber.

Retaining walls are used in areas where mining has been completed and in tunnels that are temporarily shut down for more than six months. Before constructing a retaining wall, all materials, equipment, and electrical cables in the tunnels must be removed.

Retaining walls include fixed retaining walls and temporary retaining walls. Fixed retaining walls are built to isolate tunnels and areas where mining has been completed, as well as tunnels that are temporarily shut down or not used for a period longer than six months. In the case of fire-resistant retaining walls, the wall is built of stone or solid brick, with a thickness of at least 0.55 m. In other tunnels, the retaining wall is constructed of solid brick, with a thickness of 0.45 m. Temporary retaining walls are built to isolate tunnels and mining areas where production is temporarily suspended for a period of up to six months. These walls are usually constructed of sandbags or soil, with a thickness of at least 0.6 m. The wall is built at a distance of no more than 4 m from the fresh airflow.

2.2. Classification, types and consequences of air leakage

2.2.1. Classification of air leakage

Air leakage in underground coal mines can be classified into underground air leakage, surface air leakage, and mine-wide air leakage. Underground air leakage, or in-mine air leakage, occurs within mine ventilation works such as ventilation doors, ventilation gates, retaining walls, air bridges, and previously mined-out areas. Surface air leakage, or external air leakage, occurs at the main fan station or between the ground surface and the ventilation shaft. This may involve air leaking from the surface into the ventilation shaft when exhaust fans are used, or air leaking from inside the mine to the outside when forced fans are used in the ventilation shaft. Mine-wide air leakage includes both in-mine and surface air leakage.

2.2.2. Types of air leakage

According to its distribution characteristics, air leakage may be classified as localized, continuously distributed, or mixed. Localized air leakage refers to leakage concentrated at a specific location, such as leakage through ventilation works. Continuously distributed air leakage occurs along a certain length or area, for example through parallel tunnels or excavated zones. Mixed air leakage combines both localized and continuously distributed leakage. For example, air leakage may occur through a pair of parallel tunnels excavated in a coal seam, where localized leakage takes place through the retaining walls of the connecting tunnel, while continuously distributed leakage occurs through the coal pillar between the two tunnels.

2.2.3. Consequences of air leakage

The consequences of air leakage are serious and multifaceted. First, air leakage reduces the airflow supplied to consumption places, especially at the main mining faces, where workers operate and where methane and other harmful gases are present. Second, insufficient airflow worsens workplace conditions, making the air hotter and stuffier due to inadequate dilution of contaminants and insufficient cooling, which in turn reduces labour productivity and increases the risk of heat stress and worker fatigue. Third, in mines with high methane emissions, insufficient airflow may prevent methane concentrations from being diluted below the permissible limit of 1%, and any sudden increase in methane concentration may lead to catastrophic mine fires or explosions. In addition, air leakage increases production costs, since the mine must operate the main fans at higher power in order to compensate for airflow losses and maintain the required air quantity at mining faces. This results in higher electricity consumption and greater maintenance costs. Finally, air leakage complicates ventilation management, leading to inaccuracies in the calculation and adjustment of the overall mine ventilation regime.

2.3. The influence of air leakage on the working mode of the main fan

Figure 1 shows the general schematic diagram for determining the optimal operating point of the main fan, thereby determining the fan's working mode. The graph shows that once point A is determined as the optimal operating point of the main fan, the air pressure of h_A and the airflow of Q_A generated by the fan, as well as the impeller angle and fan power, can be determined. This forms the working mode of the main fan for ventilating the entire mine.

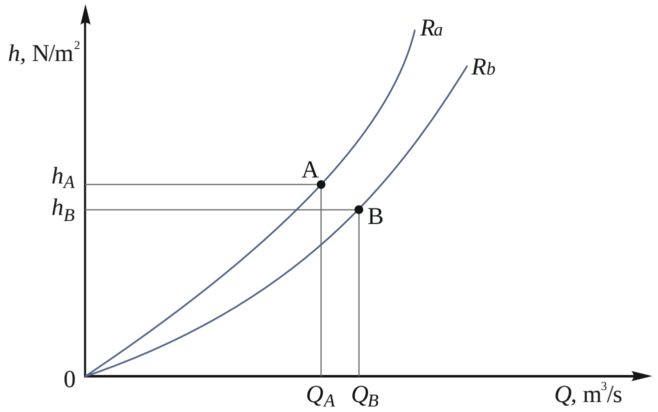


Figure 1. Influence of air leakage on the operating mode of the main fan in underground coal mines: R_a, R_b – mine resistance characteristic curves; h_A – fan pressure at operating point A; Q_A – airflow at operating point A; h_B – fan pressure at operating point B; QB – airflow at operating point B

In the case of air leakage in underground coal mines, the total resistance of the ventilation network decreases as the leakage airflow increases. This is because part of the airflow bypasses the intended working places through leakage paths, thereby changing the aerodynamic resistance of the mine ventilation network. As a result, the mine resistance characteristic curve shifts downward to curve Rb, and the fan operating point moves from A to B. Consequently, the airflow required from the fan increases from Q_A to Q_B, while the fan pressure decreases from h_A to h_B, as shown in Figure 1. This increased airflow can, in many cases, lead to motor overload or even motor burnout. In axial fans, when the operating point shifts to the right side of the characteristic curve, this risk is particularly high.

The influence of air leakage on the working mode of ventilation fans is especially negative when the main fans are connected in parallel, because the operating parameters of the fan may shift to a very low-efficiency zone.

From the practical problems mentioned above, it is clear that measures to prevent air leakage must be applied regularly to ensure ventilation safety and the stable operation of underground coal mines.

2.4. Standards for air leakage through ventilation works in underground coal mines

2.4.1. Standards in some countries around the world

In Russia, a considerable number of studies have been conducted on mine ventilation in general and on air leakage in particular. The external air leakage coefficient through ventilation shafts and air ducts is adopted according to the following values [40, 41]. For fan stations located in vertical shafts, the maximum external air leakage coefficient is $K_{rn} = 1.25$ for shafts equipped with skip hoisting, which corresponds to 25% of the airflow through the fan, and $K_{rn} = 1.20$ for shafts equipped with cage hoisting, which corresponds to 20% of the airflow through the fan. For fan stations located in a fan drift without connection to ventilation shafts, or in ventilation shafts without transport devices and sealed by ventilation gates, the maximum external air leakage coefficient is $K_{rn} = 1.10$, corresponding to 10% of the fan airflow. For fan stations located in fan drifts connected to ventilation shafts, or in ventilation shafts with transport devices, the maximum external air leakage coefficient is $K_{rn} = 1.20$, corresponding to 20% of the fan airflow. Thus, external air leakage depends on the function of the ventilation shaft connected to the fan drift where the fan station is located, particularly on whether transport devices are present, as well as on the cross-sectional area of the fan drift. According to Russian calculations, external air leakage ranges from 1.10 to 1.25, which corresponds to 10% to 25% of the fan airflow.

According to Romanian safety standards, the air leakage limits in underground coal mines are as follows [41]. Air leakage should not exceed 5% if the mine has only one airflow, that is, when air enters and leaves the mine through a single flow path. It should not exceed 10% if the mine has two airflows, that is, when air enters and leaves the mine through two different flow paths. It should not exceed 15% if the mine has more than two airflows, that is, when air enters and leaves the mine through multiple different flow paths. The air leakage standards of Romania and Russia were established during approximately the same period, namely in the 1970s and 1980s, and therefore the construction methods and the air leakage values specified in the standards are quite similar.

China currently has a highly developed mining industry. Underground coal mines in China operate under relatively favorable conditions for the application of mechanization and automation in many production stages, including mine ventilation. In China, mine ventilation is regulated on the basis of the "Safety Regulations in Coal Mining" [42] and the "Standards for Assessing the Safety Quality of Coal Mines". For underground mine ventilation in China, there are no specific standards defining the permissible level of air leakage for each individual type of ventilation structure, such as ventilation doors, air bridges, ventilation gates, or retaining walls. However, the calculation guidelines and mine safety management regulations include several relevant requirements. In particular, the ratio of required airflow, namely the airflow supplied to consumption places such as mining faces, development headings, and power stations, to the total airflow entering the mine must not be less than 85%. This means that the air leakage rate in the mine must not exceed 15%. In addition, external air leakage outside the mine, including leakage through the main fan station and fan drifts, must not exceed 5% when there is no transport equipment in the ventilation shaft and must not exceed 15% when transport equipment is installed in the ventilation shaft, as stipulated in Article 158 of the Chinese underground mining safety standard [42].

2.4.2. Standards at underground coal mines in Quang Ninh coalfield, Vietnam

In Vietnam, there are currently no national standards or industry standards specifically regulating air leakage through ventilation works. Most studies, air leakage calculation procedures, and air leakage prevention practices in Vietnam are based on inherited research results from other countries, mainly Russia and China, or on accumulated practical experience. In particular, the standards and regulations related to air leakage through ventilation works presented in specialized documents in Vietnam, as well as the standards and norms used in training materials on mine ventilation and gas management of Vietnam National Coal-Mineral Industries Holding Corporation Limited, are based on these sources. According to the mine ventilation textbook [43], the Handbook on Underground Mine Ventilation, Tunnels and Fans, and the training materials on ventilation work of Vietnam National Coal-Mineral Industries Holding Corporation Limited [44], air leakage through ventilation works may be summarized as follows.

For retaining walls, the air leakage rate ranges from 0.11 to 0.50 m^3/s. For retaining walls with ventilation doors, the air leakage rate ranges from 0.67 to 2.60 m^3/s. For air bridges, the air leakage rate ranges from 0.58 to 1.25 m^3/s. External air leakage in ventilation shafts depends on the degree of sealing of the transport shaft, whether skips or cages are used, and the external air leakage coefficient ranges approximately from 10% to 30% of the airflow entering the mine.

3. Results and discussion

3.1. Air leakage through ventilation works in underground mines of the Quang Ninh coalfield

Field surveys, measurements, and data collection on air leakage through ventilation works were conducted at 10 underground coal mines in the Quang Ninh coalfield, including Mao Khe, Nam Mau, Uong Bi, Nui Beo, Hon Gai, Quang Hanh, Duong Huy, Mong Duong, Khe Cham, and Ha Long coal mines. These are all large-scale mines belonging to Vietnam National Coal-Mineral Industries Holding Corporation Limited. Survey and measurement data were collected at the mines for ventilation doors, ventilation gates, retaining walls, and gates at the fan stations representing external air leakage.

Based on measurements taken at many different locations, the collected data covered a certain range of values, from which the corresponding average values were determined. A summary of the collected data on air leakage through ventilation works at underground coal mines in the Quang Ninh, is presented in Table 1 [45, 46]. Based on these air leakage data, the graph of air leakage through the investigated ventilation works is shown in Figure 2.

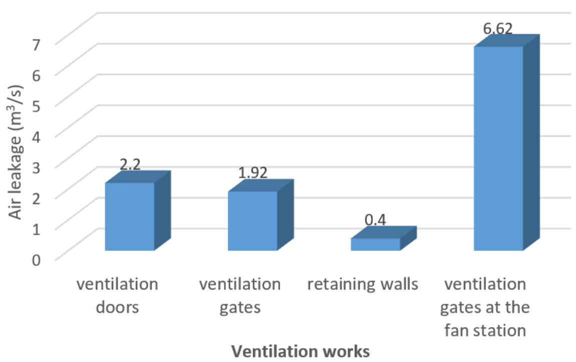


Figure 2. Graph of air leakage through ventilation works in underground coal mines in the Quang Ninh coalfield

Figure 2 shows that external air leakage through the main fan stations is the highest among the investigated ventilation works in underground coal mines of the Quang Ninh coalfield, with an average value of 6.62 m^3/s. Air leakage through ventilation doors ranks second, averaging 2.2 m^3/s, followed by ventilation gates, with an average value of 1.92 m^3/s. The lowest air leakage is observed through retaining walls, with an average value of 0.4 m^3/s.

Table 1. Summary of air leakage levels through ventilation works in underground coal mines in the Quang Ninh coalfield, Vietnam

No.	Coal mine	Air leakage through ventilation works, m^3/s				Note
		Doors	Gates	Walls	Gates at fan stations	
1	Mao Khe	1.8-2.0	1.6-2.0	0.1-0.2	3.8-14.2	Range of values
		1.9	1.8	0.15	8.25	Average
2	Nam Mau	1.8-2.2	1.6-2.0	0.0-0.5	4.6-6.5	Range of values
		2.0	1.8	0.25	5.55	Average
3	Uong Bi	1.7-2.7	1.9-2.7	0.0-0.5	1.5-7.6	Range of values
		2.2	2.3	0.25	3.3	Average
4	Nui Beo	1.8-2.3	1.7-2.5	0.0-0.25	4.5-13.9	Range of values
		2.05	2.1	0.12	7.7	Average
5	Hon Gai	1.8-2.5	1.7-2.4	0.0-0.5	1.5-12.6	Range of values
		2.15	2.05	0.25	4.7	Average
6	Quanh Hanh	1.6-2.6	1.7-2.6	0.0-0.25	2.8-7.3	Range of values
		2.1	2.15	0.12	3.6	Average
7	Duong Huy	1.8-2.8	1.7-2.6	0.25-0.5	2.0-15.5	Range of values
		2.3	2.15	0.37	7.0	Average
8	Mong Duong	2.0 -2.4	1.7-2.5	0.0-0.5	2.8-15.0	Range of values
		2.2	2.1	0.25	7.7	Average
9	Khe Cham	1.8 -2.0	1.2-2.0	0.0-0.5	3.5-18.5	Range of values
		1.9	1.6	0.25	11.0	Average
10	Ha Long	2.2-2.5	1.6-2.5	0.0-0.8	6.1-8.8	Range of values
		2.35	2.05	0.4	7.45	Average
General summary		1.6-2.8	1.2-2.7	0.0-0.8	1.5-18.5	Range of values
		2.2	1.92	0.4	6.62	Average

3.2. Assessment of air leakage through ventilation works

3.2.1. General assessment of air leakage levels through ventilation doors

According to the data presented in Table 1, the level of air leakage through ventilation doors at underground coal mines in the Quang Ninh coalfield depends on the type of door, whether temporary or permanent, the mode of transport through the door, whether for personnel only or for vehicles, the material of the door, the number of door leaves, whether the door is opened and closed manually or automatically, and whether the door is guarded.

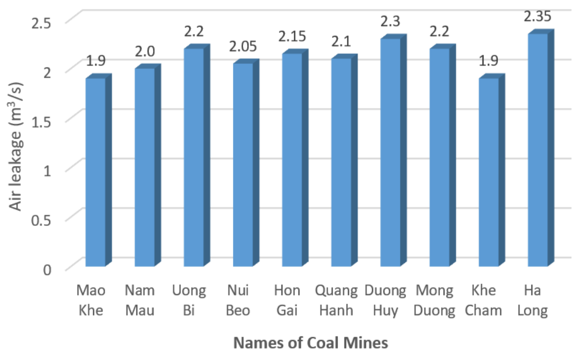
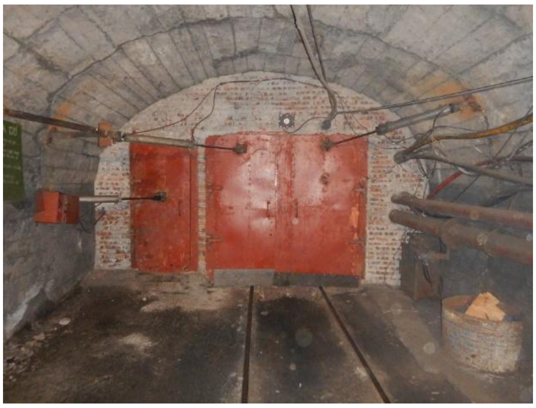


Figure 3. Graph of air leakage through ventilation doors at underground coal mines in the Quang Ninh coalfield

Thus, the survey data collected from 10 underground coal mines in the Quang Ninh coalfield, as presented in Table 1, show that air leakage through ventilation doors ranges from 1.6 to 2.8 m^3/s, with an average value of 2.2 m^3/s. The survey was conducted on doors used for air separation, with brick walls and iron doors, most of which are manually opened and closed without guards. Figure 3 shows that Ha Long Coal Mine has the highest air leakage through ventilation doors, with an average value of 2.35 m^3/s.

Mao Khe and Khe Cham coal mines have the lowest air leakage through ventilation doors, with an average value of 1.9 m^3/s. Other coal mines, including Nam Mau, Nui Beo, Hon Gai, Quang Hanh, Uong Bi, and Mong Duong, which were surveyed and measured in the field, showed similar values ranging from 2.0 to 2.2 m^3/s. Images of some ventilation doors surveyed at underground coal mines in the Quang Ninh coalfield are shown in Figure 4 [46].

(a)



(b)

Figure 4. Images of two typical ventilation doors at two underground coal mines in the Quang Ninh coalfield: (a) – Vang Danh; (b) – Mong Duong

3.2.2. General assessment of air leakage levels through ventilation gates

Ventilation gates located in the main transport tunnels, where the electric train system operates, are usually permanently constructed with two to three gates, most commonly two, and can be opened and closed either manually or automatically. Field survey results from the mines, as shown in Table 1 and Figure 2, indicate that air leakage through permanent ventilation gates ranges from 1.2 to 2.7 m^3/s, with an average value of 1.92 m^3/s. Figure 5 shows that Uong Bi Coal Mine has the highest air leakage through ventilation gates, with an average value of 2.3 m^3/s.

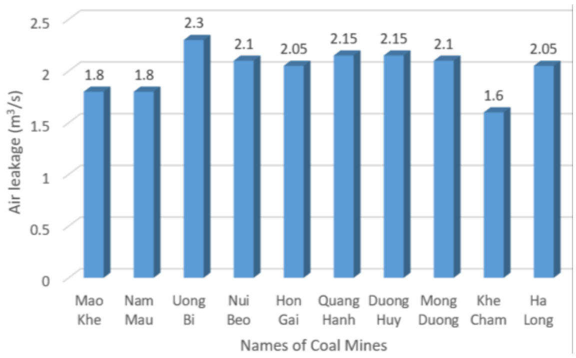


Figure 5. Graph of air leakage through ventilation gates at underground coal mines in the Quang Ninh coalfield

Khe Cham Coal Mine has the lowest air leakage through ventilation gates, with an average value of 1.6 m^3/s. Mao Khe and Nam Mau coal mines have an average air leakage of 1.8 m^3/s. Other coal mines, including Hon Gai, Ha Long, Nui Beo, Mong Duong, Quang Hanh, and Duong Huy, which were surveyed and measured in the field, showed similar values ranging from 2.05 to 2.15 m^3/s. Figure 6 shows a ventilation gate surveyed at Mong Duong Coal Mine [46].

Figure 6. Image of a manually operated ventilation gate with a brick wall and iron frame at the +30 tunnel in the Canh Dong area of Mong Duong Coal Mine

3.2.3. General assessment of air leakage levels through retaining walls

Retaining walls are usually constructed of brick, with or without plastering, or of concrete. In some coal mines with self-igniting properties, permanent walls are also constructed of fly ash. Temporary retaining walls are often built using sandbags. According to the survey data from coal mines in the Quang Ninh coalfield presented in Table 1.

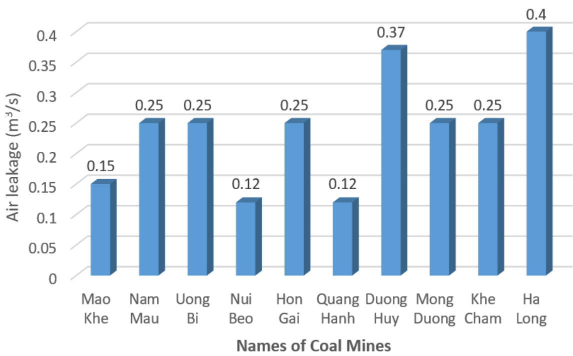


Figure 7. Graph of air leakage through retaining walls at underground coal mines in the Quang Ninh coalfield

Air leakage through retaining walls is relatively low, and at many locations no leakage was recorded. At locations where leakage does occur, it mainly appears along the sides of the tunnel or through cracks in the wall, ranging from 0.0 to 0.8 m^3/s, with an average value of 0.12 m^3/s.

Figure 7 shows that Ha Long Coal Mine has the largest air leakage through the retaining walls, averaging 0.4 m^3/s, followed by Duong Huy Coal Mine, averaging 0.37 m^3/s. Nui Beo and Quang Hanh Coal Mines have the smallest air leakage through the retaining walls, averaging 0.12 m^3/s. Nam Mau, Uong Bi, Hon Gai, Mong Duong, and Khe Cham Coal Mines all have similar air leakage, averaging 0.25 m^3/s.

3.2.4. General assessment of the level of external air leakage through main fan stations

In underground coal mines, most main fan stations have fan drifts connected to ventilation openings, including inclined shafts, horizontal roadways, or vertical shafts. At the entrances to these ventilation openings, air gates are usually installed. The level of air leakage through these gates depends on the mode of transport passing through them, whether electric trains, conveyor systems, or only personnel, as well as on whether the gates are opened and closed manually or automatically. Air leakage at these locations is usually quite significant because of the large pressure difference between the outside atmosphere and the inside of the mine openings. This is also referred to as air leakage through the air gates at the main fan stations.

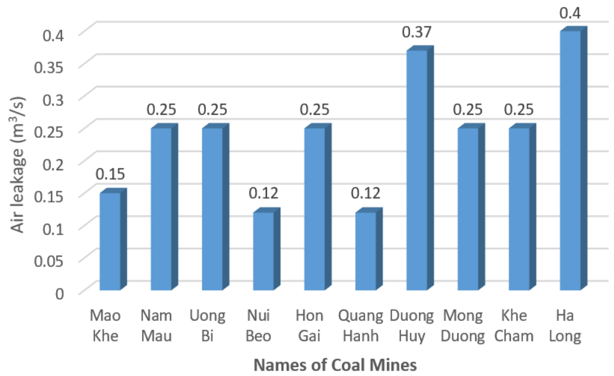


Figure 8. Graphs of external air leakage through main fan stations at underground coal mines in the Quang Ninh coalfield

According to the survey data collected at underground coal mines in the Quang Ninh coalfield, as presented in Table 1, the external air leakage at the main fan stations ranges from 1.5 to 18.5 m^3/s, with an average value of 6.62 m^3/s, corresponding to 1.5 to 22.6% of the main fan airflow, with an average of 9.16%.

Figure 8 shows that Khe Cham Coal Mine has the highest external air leakage, with an average value of 11.0 m^3/s, followed by Mao Khe Coal Mine, with an average value of 8.25 m^3/s. Uong Bi and Quang Hanh coal mines have the lowest external air leakage, with average values of 3.3 and 3.6 m^3/s, respectively. Duong Huy, Ha Long, Nui Beo, and Mong Duong coal mines all show comparable external air leakage values, ranging from 7.0 to 7.7 m^3/s. These results indicate that external air leakage at main fan stations is a major contributor to overall air loss in the ventilation systems of coal mines in the Quang Ninh coalfield and should therefore be considered a priority target for control and mitigation.

3.3. Proposed solutions to reduce air leakage through ventilation works in underground coal mines in the Quang Ninh coalfield

3.3.1. Solutions to reduce air leakage through ventilation doors

Ventilation doors must be constructed in accordance with the approved design and installed at the locations specified in the ventilation scheme. A safe clearance around the doors must be maintained in order to ensure the safe movement of personnel and transport equipment through the tunnels.

All ventilation doors must provide the highest possible airtightness of both the door frame and the door leaf. The joints between the door structure and the roof and sidewalls of the tunnel must be carefully sealed. At the floor contact, flexible materials such as rubber gaskets should be used in order to prevent air leakage. Permanently installed doors in main tunnels should be equipped with double-sided hinges or horizontal sliding mechanisms to facilitate airflow reversal when required.

Ventilation doors installed in main airways and ventilation tunnels must be constructed in a strong and reliable manner and should include at least two door sets forming an airlock in order to ensure continuous closure during operation. The installation of ventilation doors in inclined tunnels used for hoisting transport should be prohibited. In exceptional cases, such installation may only be allowed on the basis of a special design and an authorized hoisting schedule approved by the Director.

Before construction, the support system should be carefully inspected, and the condition of the rock mass in the roof, sidewalls, and floor of the tunnel should be checked. Coal and rock debris must be removed from the site in order to provide sufficient working space and avoid obstructing the movement of personnel and vehicles. The concentrations of CH_4, CO_2, and CO, as well as the temperature at the planned construction site, must also be checked before work begins.

For permanent doors intended for long-term service, the construction site should be selected in areas where the roof, floor, and sidewalls are geologically stable. If construction in unstable ground conditions cannot be avoided, additional reinforcement measures must be implemented to ensure sufficient compaction of the surrounding rock mass at the door site and to prevent air leakage through cracks.

Construction methods must be selected carefully, and the approved design must be strictly followed during construction. If any changes to the construction plan are required, they must be reported to the ventilation manager for review and approval.

The construction of permanent ventilation doors generally includes inspection of the selected location, construction of the wall and assembly of the door frame, and completion of the frame followed by installation of the ventilation door.

The construction of ventilation doors must be directly supervised by a responsible person who gives instructions and continuously monitors the condition of the tunnel and surrounding walls in order to respond promptly to any unsafe situations. During construction, any person passing through the work area must obtain permission from the supervisor. Before passage is allowed, the ventilation door structure must be checked to ensure safe conditions. Passage through the construction zone should be carried out carefully and without delay.

During construction, all works must comply with the approved technical measures, the national technical regulations and safety standards for underground coal mining under QCVN 01:2011/BCT issued by the Ministry of Industry and Trade on February 15, 2011, and other related procedures and regulations [47].

From the technical point of view, the ventilation door must open and close smoothly. It may be operated manually, but it should also be capable of closing automatically under its own weight due to the pressure difference. A gasket, preferably made of rubber, should be installed between the frame and the door leaf in order to reduce air leakage. The door leaf should be smooth and flat, while the door wall should be constructed of fire-resistant material and built in competent rock without cracks.

During operation, ventilation doors without a designated operator should be used only after the surrounding area has been checked for obstacles or equipment preparing to pass through. If transport equipment is approaching, priority should be given accordingly. If the passage is clear, the door may be opened for movement through the opening. For ventilation doors with a designated operator, all personnel and vehicles must obtain permission and follow the instructions of the operator before passing. If a train requests passage and an inspection shows that the route ahead is obstructed by equipment or another train, the train must be instructed to stop and wait until the route is clear before the door is opened.

The fabrication and construction of ventilation doors are usually carried out by the ventilation workshop. After installation is completed, responsibility for management and maintenance must be formally handed over to the relevant production unit or workshop within the mine management area, and this handover must be documented. If any ventilation door is damaged or if air leakage exceeds the permissible level, the ventilation workshop must be informed immediately so that repair can be carried out. During repair or replacement, temporary barriers or partitions should be installed in order to minimize air leakage and maintain production conditions. During production shifts, the ventilation section should carry out regular inspections of ventilation doors to assess their operating condition and physical state at each location. If any door is found to be damaged, deformed, or non-compliant with technical requirements, a report must be issued to the responsible unit, clearly stating the cause of the violation, identifying responsibility, and requiring immediate corrective action.

On a weekly basis, the ventilation section should compile reports on all detected violations and submit them to the Mine Ventilation and Drainage Department. These reports are then forwarded to the Director, who determines the corresponding disciplinary measures. The final penalties may be considered during monthly performance evaluations and product acceptance inspections, depending on the seriousness of each case.

3.3.2. Solutions to reduce air leakage through ventilation gates

The construction and installation of ventilation gates are generally based on the same principles as those applied to ventilation doors. However, some additional requirements should be considered during the management, construction, and operation of ventilation gates. In cases where the tunnel is used only for personnel passage, the distance between the two gates should be at least 5 m, and such gates are usually manually operated. When trains pass through the tunnel, the distance between the two gates must be greater than the maximum train length, and automatic gates should be installed.

The operating principles for ventilation gates are similar to those applied to permanent ventilation doors. However, during passage through a ventilation gate, each gate must be opened separately. After passing through the first gate, it must be closed securely before the second gate is opened. Opening both gates at the same time is prohibited because it causes air leakage. If the ventilation gate includes a side door for personnel passage, only this side door should be used, except in cases where bulky materials or equipment are being carried or transported.

Ventilation gates installed in mine roadways used for electric train transport are usually managed, maintained, and operated by the mine transport sections. Ventilation gates located in tunnels used only for personnel passage are generally managed, maintained, and operated by the ventilation sections.

3.3.3. Solutions to reduce air leakage through ventilation shafts

At main fan stations where the fan drift is connected to tunnels or ventilation shafts, ventilation gates are installed at the top of the tunnels or at the top of the ventilation shafts. To reduce air leakage through ventilation shafts, several basic solutions should be implemented.

Additional ventilation gates may be installed in the ventilation shafts, with at least two gates provided where possible. At the same time, the construction quality, installation technique, and sealing performance of these ventilation gates, as well as the sealing of covers in vertical shafts, should be improved.

Regular inspection and timely repair of any defects are also necessary, since the pressure difference on the two sides of the ventilation gates is usually very large.

The ventilation gates at the top of ventilation shafts should be designed with auxiliary doors for personnel access, and automatic opening and closing gates should be prioritized. In addition, in order to reduce air leakage through cracks in the surrounding rock into the ventilation shafts, the upper section of the shaft or connecting opening should be concreted.

Ventilation shaft entrances must be strictly controlled, and personnel and vehicles should be allowed to pass only with authorization from the responsible guard. Air leakage through ventilation shafts usually accounts for the major part of the external air leakage of a mine. In addition, significant leakage may also occur through fan station buildings, inspection doors of fan shafts, and fan blades. In shallow mines, further external leakage may occur through surface fissures or cracks extending into the mine workings.

3.3.4. Solutions to reduce air leakage through retaining walls (stoppings)

Retaining walls, or ventilation stoppings, are constructed to isolate tunnels after fire incidents or to seal off temporarily suspended roadways. The construction and opening of these isolation structures must strictly follow the approved plans and ensure compliance with safety regulations, technical standards, and operating procedures. To reduce air leakage through these structures, several fundamental measures should be implemented.

During construction, the responsible section must strictly comply with the approved technical measures, the national technical regulations and standards on safety in underground coal mining under QCVN 01:2011/BCT issued by the Ministry of Industry and Trade on February 15, 2011, and other related procedures and regulations [47].

The construction of the retaining wall, from the foundation to the full perimeter, must follow closely the sides and roof of the tunnel. The wall must be straight, flat, and airtight. It should also be equipped with pipes for monitoring or controlling the gases inside the sealed area. The construction of retaining walls must be supervised, and the condition of the tunnel and the wall must be continuously monitored in order to address any situations that may arise. Each retaining wall should also be numbered sequentially.

Fire-resistant materials that satisfy the required technical standards should be used for the construction of retaining walls, and the wall thickness should not be less than 500 mm.

The wall surface must be free of cracks, and any gaps between the wall and the sides or roof of the tunnel must be carefully sealed. If necessary, one or more layers of coating may be applied to the wall surface in order to improve its airtightness and smoothness and thereby reduce air leakage.

3.3.5. General solutions related to organization and management

Air leakage in underground mines results from a variety of factors, primarily pressure differences along leakage paths, improper construction or operation of ventilation structures, and inadequate methods of mine pressure control. Other important causes include insufficient coal pillar width between parallel roadways and surface subsidence or fracturing caused by mining activities.

Such leakage significantly reduces the supply of fresh air to working faces, leading to the accumulation of hazardous gases and coal dust, elevated temperatures, and reduced labour productivity, all of which adversely affect workers' health. In addition, air leakage forces ventilation fans to operate at higher capacities, resulting in considerable energy losses. Therefore, in addition to specific technical measures for each ventilation structure, several general organizational and management solutions should be applied.

A rational ventilation scheme and ventilation method should be selected, since air leakage in the mine is generally lower with a side ventilation scheme and higher with a central ventilation scheme. Proper planning of mining operations and the selection of appropriate technical solutions for the mine are also important, because the mining sequence and mining method have a strong influence on the level of air leakage.

Main roadways, which are intended for long-term use, should be excavated in rock whenever possible. Old and unused workings should either be demolished or isolated by retaining walls. Appropriate mine pressure control methods should also be applied in order to reduce air leakage into mined-out areas. To reduce air leakage in ventilation shafts, the number and quality of ventilation doors in inclined shafts should be increased where necessary, and the sealing quality of vertical shafts should be improved.

An important management requirement is the comprehensive improvement of the quality of mine ventilation safety personnel. Human resources are a key factor in mine ventilation safety management, and the effectiveness of ventilation safety largely depends on the competence of the responsible staff. A mine ventilation manager should have a thorough understanding of ventilation safety and of the risks associated with ventilation management. Improving the quality of mine ventilation managers requires better professional education and training in management, as well as a stronger sense of responsibility and professional ethics, with safety regarded as a primary obligation.

Mine ventilation safety measures should also be inspected and evaluated regularly. The different types of work related to mine ventilation management should be classified scientifically, with clear and logical functions, and the allocation of authority, responsibility, and benefits should be optimized according to these functions. Ineffective or inappropriate management measures should be identified and eliminated.

It is also necessary to develop and improve the relevant system of standards and to implement mine ventilation safety management in accordance with established standards. Effective ventilation management requires standardized procedures at different stages, including the installation and operation of main fan stations, local fans, and retaining walls. Standardization of work content and its implementation can improve the quality of ventilation management and ensure more accurate assessment of work quality.

Strict inspection and evaluation must also be ensured at the design stage. In order to improve the quality of the working environment and continuously comply with mine safety requirements, the design of mine ventilation facilities must strictly follow the relevant safety and design regulations.

Daily ventilation safety management is equally important. Mine ventilation equipment should be maintained regularly, and dust, dirt, and other deposits on ventilation equipment should be cleaned in a timely manner. Damaged ventilation equipment must be repaired or replaced promptly. Ventilation works such as doors, gates, and retaining walls should also be inspected regularly so that any defects or malfunctions can be detected and corrected in time.

Finally, a rational mining plan should be developed in order to ensure the stability of the mine ventilation network.

3.4. Proposed designs for ventilation works to mitigate air leakage applicable to some underground mines in the Quang Ninh coalfield

3.4.1. Ventilation gates

Ventilation gates are ventilation structures constructed to separate fresh air from return air, especially in tunnels where people and vehicles frequently pass through. To effectively isolate airflows and reduce air leakage, at least two ventilation gates should be installed together in order to create an air chamber.

Ventilation gates can be divided into two main types, namely in-mine ventilation gates and ventilation gates installed at the mine entrance in connection with fan drifts. In-mine ventilation gates are usually constructed at the main transport tunnels of the mine, where transport density is high or where human traffic is frequent. Based on the survey results and the assessment of air leakage in underground mines of the Quang Ninh coalfield, air leakage through ventilation gates mainly occurs in tunnels with a high level of electric train traffic and usually accounts for 15-20% of the airflow to the fan. Therefore, the authors propose a design of an in-mine ventilation gate system for electric train transport tunnels in order to reduce air leakage, as shown in Figure 9.

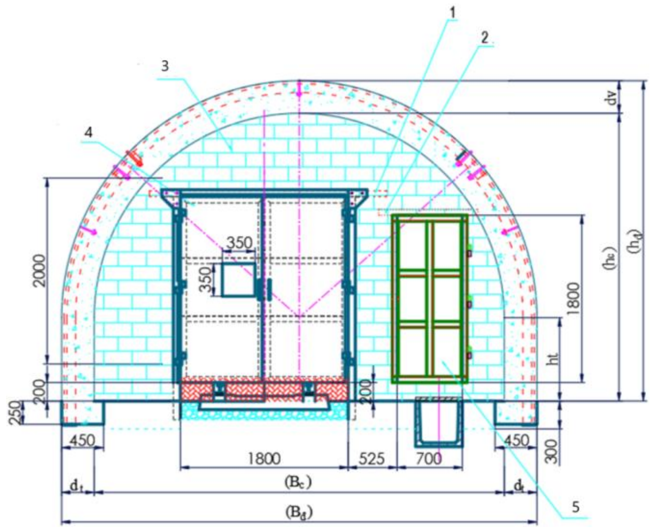


Figure 9. Schematic design of steel ventilation gates installed in a train transport ventilation shaft: 1 – steel beam U160×68×5, length 2.6 m; 2 – steel beam U160×68×5, length 1.1 m; 3 – brick wall; 4 – ventilation gate; 5 – secondary door for personnel access

3.4.2. Ventilation doors

Ventilation doors are installed in tunnels to prevent or regulate airflow while still allowing passage for people and vehicles through opening and closing.

Based on surveys and assessments of the current state of air leakage in underground mines of the Quang Ninh coalfield, air leakage is often high when ventilation doors are installed in tunnels where electric trains, conveyor belts, or scraper conveyors are in operation. Therefore, the authors propose a model design of ventilation doors for tunnels equipped with electric trains, conveyor belts, and scraper conveyors in order to reduce air leakage. This ventilation door design is shown in Figure 10.

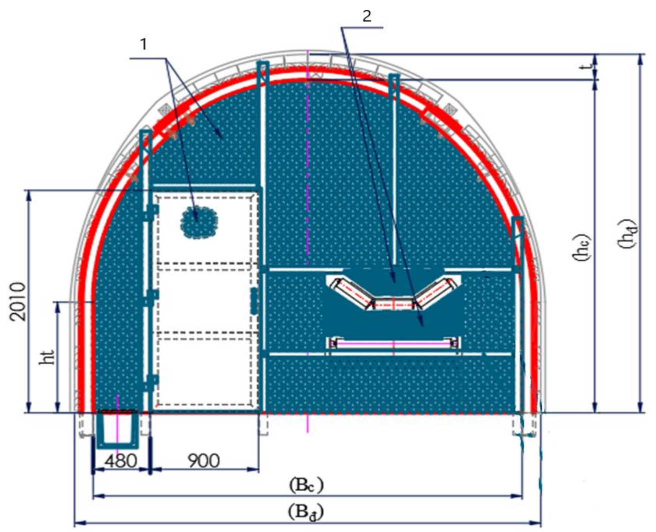


Figure 10. Schematic design of a steel ventilation door installed in a conveyor belt transport tunnel: 1 – sheet metal with a thickness of 0.5 mm; 2 – conveyor belt cover, usually made from old conveyor belts

3.4.3. Retaining walls

Retaining walls are used to isolate areas where mining has been completed, as well as tunnels that are no longer in use or are temporarily out of service (Figure 11).

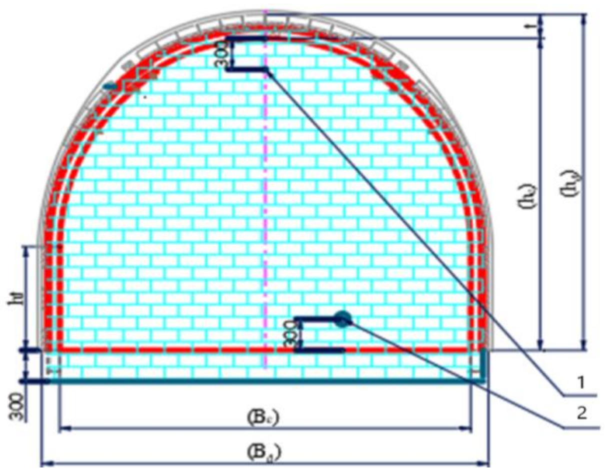


Figure 11. Schematic design of a permanent brick retaining wall: 1 – PVC pipe with a diameter of 21 mm and a shut-off valve, used for gas measurement; 2 – PVC pipe with a diameter of 100 mm, used for drainage

The authors propose a typical design of a permanent brick retaining wall to reduce air leakage, as shown in Figure 11. Permanent retaining walls are usually constructed of brick or concrete, whereas temporary retaining walls are often made of sandbags.

4. Conclusions

Ventilation networks in underground coal mines of the Quang Ninh coalfield, operated by Vietnam National Coal-Mineral Industries Holding Corporation Limited, are characterized by a high level of complexity, ranging from moderate to very complex, regardless of the production scale of the mine.

The main ventilation works used in these mines include ventilation doors, ventilation gates, and retaining walls, whereas air bridges are practically absent in this coalfield. Field surveys and measurement data indicate that air leakage occurs in most of these structures, with the highest values recorded for ventilation doors, averaging 2.15 m^3/s, and ventilation gates, averaging 1.92 m^3/s. In contrast, retaining walls are generally well constructed and properly maintained, resulting in relatively low air leakage, with an average value of only 0.12 m^3/s.

Surface air leakage occurs mainly through the ventilation gates located at shaft entrances connected to the main fan stations. The average external air leakage was measured at 6.62 m^3/s, which corresponds to approximately 9.16% of the total fan airflow.

Although the air leakage rates recorded in the Quang Ninh coalfield are slightly higher than those specified in some international standards and guidelines, the difference is not considerable. In particular, the performance of retaining walls is close to international good practice due to their adequate construction quality and effective management.

Ventilation works play an important role in maintaining mine air quality and operational efficiency. To reduce air leakage, a comprehensive technical approach is required, covering all stages from design and construction to inspection, maintenance, and operation, with due consideration of the specific characteristics of each type of ventilation work. Such measures are essential for improving airflow distribution and enhancing the overall safety of underground coal mining operations.

Author contributions

Conceptualization: CVD; Data curation: CVD, TTV; Formal analysis: CVD, TTV; Investigation: CVD, TTV; Methodology: TTV; Project administration: CVD, TTV; Resources: CVD, TTV; Supervision: TTV; Validation: CVD; Visualization: CVD; Writing – original draft: TTV; Writing – review & editing: CVD, TTV. All authors have read and agreed to the published version of the manuscript.

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Conflicts of interest

The authors declare no conflict of interest.

Data availability statement

The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

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Көмір шахталарындағы ауа шығынын азайту: Вьетнамдағы Куангнинь көмір бассейні мысалында

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Аңдатпа. Жерасты көмір шахталарындағы желдету жүйелерінің тұрақтылығы мен тиімділігі өндіріс қауіпсіздігін қамтамасыз ету және жұмысшылардың денсаулығын қорғау үшін шешуші маңызға ие. Ауа ағуы тазарту кенжарлары, тұйық қазбалар және ірі жерасты камералары сияқты жұмыс аймақтарына таза ауаның жеткізілу тиімділігін төмендетіп қана қоймай, көмірдің өздігінен жануы және метанның жиналуы сияқты жарылысқа әкелуі мүмкін қауіпті құбылыстардың туындауына да ықпал етеді. Сонымен қатар, ауа ағуы бас желдеткіш қондырғылардың жұмысы кезінде энергия тұтынуды айтарлықтай арттырады. Осыған байланысты жерасты көмір шахталарындағы ауа ағуын азайтуға бағытталған шешімдерді зерттеу және әзірлеу қажеттілігі туындайды. Тау-кен жұмыстарының сызбасын, желдету сызбасын және қолданыстағы желдету құрылыстарын талдау негізінде авторлар натурлық зерттеулер, өлшеулер, талдау және бағалау жұмыстарын жүргізді. Бұл шахталардың желдету құрылыстары арқылы болатын ауа ағуын азайту жөніндегі шараларды ұсынуға мүмкіндік берді. Сонымен қатар, Вьетнамдағы Куангнинь көмір бассейнінің жерасты көмір шахталарында қолдануға болатын желдету шлюздері, желдету есіктері және оқшаулағыш бөгеттер үшін конструктивтік шешімдер ұсынылды. Зерттеуде деректерді жинау, натурлық зерттеу, аспаптық өлшеу, шахталық талдау, сондай-ақ алынған нәтижелерді талдау және бағалау әдістері қолданылды. Ұсынылған шешімдер шахталық өндірісте енгізіліп, оң нәтижелер көрсетті, оның ішінде ауа ағуын азайту, желдету тиімділігін арттыру, бас желдеткіш қондырғылардың жұмыс режимдерін жақсарту және жалпы шахта бойынша желдету шығындарын қысқарту нәтижелері байқалды. Осы зерттеудің нәтижелері жерасты көмір шахталарында желдету жоспарларын әзірлеуге, сондай-ақ бүкіл шахта көлемінде ауа ағуын азайтуға бағытталған тиісті желдету құрылыстарын таңдау және орнату үшін негіз бола алады.

Негізгі сөздер: *ауа ағуы, ауа ағуын төмендету, желдету құрылыстары, негізгі желдеткіш қондырғылар, көмір шахталары, Куангнинь көмір бассейні.*

Снижение утечек воздуха в угольных шахтах: на примере угольного бассейна Куангнинь, Вьетнам

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Аннотация. Стабильность и эффективность вентиляционных систем подземных угольных шахт имеют решающее значение для обеспечения безопасности производства и защиты здоровья работников. Утечки воздуха не только снижают эффективность подачи свежего воздуха к рабочим зонам, включая очистные забои, тупиковые выработки и крупные подземные камеры, но и способствуют возникновению таких опасных явлений, как самовозгорание угля и накопление метана, которые могут привести к взрывам. Кроме того, утечки воздуха значительно увеличивают энергопотребление при работе главных вентиляторов. В связи с этим возникает необходимость исследования и разработки решений, направленных на снижение утечек воздуха в подземных угольных шахтах. На основе анализа схемы горных работ, схемы вентиляции и существующих вентиляционных сооружений авторами были проведены натурные обследования, измерения, анализ и оценка, что позволило предложить меры по снижению утечек воздуха через вентиляционные сооружения шахт. Кроме того, предложены конструктивные решения для вентиляционных шлюзов, вентиляционных дверей и изоляционных перемычек, которые могут быть применены на подземных угольных шахтах угольного бассейна Куангнинь, Вьетнам. В исследовании использованы методы сбора данных, натурных обследований, инструментальных измерений, шахтного анализа, а также анализа и оценки полученных результатов. Предложенные решения были внедрены в шахтное производство и показали положительные результаты, включая снижение утечек воздуха, повышение эффективности вентиляции, улучшение режимов работы главных вентиляторов и сокращение вентиляционных затрат по шахте в целом. Результаты данного исследования также могут служить основой для разработки вентиляционных планов на подземных угольных шахтах, а также для выбора и установки соответствующих вентиляционных сооружений, направленных на снижение утечек воздуха в масштабе всей шахты.

Ключевые слова: *утечки воздуха, снижение утечек воздуха, вентиляционные сооружения, главные вентиляторные установки, угольные шахты, угольный бассейн Куангнинь.*

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