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Research on local cold airflow supply methods in designing cooling solutions for longwall faces in underground coal mines

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ABSTRACT

Workers in underground coal mines are always at risk of heat shock due to high temperatures and narrow spaces. To reduce the temperature in the longwall faces, some mines have used air conditioners to increase the cooling capacity, creating a better working environment for miners. However, the current method has wasted significant cooling capacity for short-distance tunnels while providing a negligible cooling effect for remote longwall face areas. To resolve this problem, the cooling solution using cold airflow distributed at local points has been studied. The essence of this solution is to direct all cold air from the air conditioner into the air duct and only supply it to the necessary locations. The cold airflow from the air duct is sprayed into the main airflow to reduce the temperature locally for each miner's working position. The cold airflow can be actively adjusted to correspond to the cooling zone in the tunnel's upper, middle, or lower part and longwall face. The effect achieved is to reduce cold air loss, increase the air conditioner's life by installing it in a favorable environment, and directing the cold airflow through the duct to the necessary place. An experimental study using the airflow from the air compressor also reduced $1.1^{0}C$ over a local range of 5 m in the LC-I-9-24B longwall face at the Nam Mau coal mine. This clarifies the applicability of cold airflow at local points and introduces the direction of improving the cooling efficiency of air conditioners in underground coal mines.

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1. Introduction

Energy security is one of the core issues of the national economy. Among the main energy sectors, the Vietnamese coal industry is an important link to maintain and ensure energy for production development. According to the planning (Prime Minister, 2023), Vietnam's underground coal mines are moving towards deep development, typically at Vang Danh coal mine, which is developing to a depth below -175 m, Mao Khe coal mine to a depth below -150 m, and a depth below -300 m at Nga Hai coal mine. In addition, underground mining activities are also taking place at deep coal mines such as Ha Long coal mine (-350 m), and Ha Lam coal mine (-300 m) and shortly will develop to -500 m. Workers at these depths not only the danger of mine pressure but also a heightened risk of thermal shock. In high-temperature environments, miners' health is seriously threatened affecting labor productivity, and the production efficiency of enterprises declines (Gibb et al., 2024; Su et al., 2009).

In Vietnam's underground coal mines, the main principle for controlling the underground thermal environment is the distribution of mine airflow. Controlling the pressure of the airflow in a continuous homogeneous environment is the basis of this method (Kamyar et al., 2016; Brodny and Tutak, 2017). However, in areas far from the center of the mine (from 3÷5 km), the airflow cannot reach the longwalls effectively, thus failing to ensure the cooling effect at the workers' workplace. Therefore, the current cooling scheme in underground coal mines needs to be adjusted, and the air distribution more suitable to meet the cooling requirements at the workers' workplaces (Szlązak et al. 2016; Nikolaev et al., 2017). This approach is ideal for the actual characteristics of the underground coal mining environment, providing a more effective and sustainable cooling solution for mining enterprises.

Currently, underground coal mines in Vietnam use the traditional cooling mode of fresh air taken from the atmosphere through fan stations. The operating mode of the main fan and the ability to regulate airflow distribution will determine the efficiency of mining air cooling. In recent years, some underground coal mines in Vietnam have installed additional MK-300 air conditioners in the tunnel to provide cooling for the longwall faces (Dao et al., 2017; 2019; Nguyen and Nguyen, 2019). The MK-300 air conditioner is located at the roadway and then pushes the cold air along the entire cross-section of the roadway leading to the longwalls face. According to temperature control results at the mines, the cooling capacity of this method is not effective, specifically: at the mechanized longwall face of the coal seam 11 in the Ha Lam coal mine, the temperature only decreased by 1.4÷1.7^{0}C, and this value only reached 1.3^{0}C at the longwall face I-11-3 in Khe Cham I area of Ha Long coal company. One of the reasons for the ineffective cooling is the overly wide dispersion range of the cooling area behind the MK-300 air conditioner. In many cases, this method has wasted a large amount of cooling capacity for the short-range tunnels while providing an insignificant cooling effect to distant areas. To increase the cooling capacity, the MK-300 air conditioner is placed closer to the longwall face. However, this means that the machine must be placed in a narrow space, with high dust and humidity. These conditions are not good for the air conditioner to work effectively. The machine often has problems when applied at the Ha Lam and Ha Long coal mines. To overcome the above disadvantages, a local cooling mode using cold airflow directed to the required points of the workers' working positions has been proposed to reduce the temperature and meet the workers' need for thermal comfort. Two main advantages determine the effectiveness of this solution, including: (1) providing accurate cold airflow to each specific working position of the worker through a closed air duct, reducing cold air loss; (2) routing cold airflow through the air duct behind the MK-300 air conditioner allows for the selection of a location to place the machine in a spacious area with low humidity and minimal dust-conditions that favor effective operation and prolong the machine's lifespan.

According to the proposed cooling mode, the method uses a local air distribution form based on segmented points. This method aims to provide cold air to cool only the working position of the worker, avoiding waste of cooling capacity in ineffective cooling zones. In addition, the efficiency is considered taking into account the characteristics of the remote underground space, the long and narrow tunnel, and the presence of dispersed workers. The interaction between the cold airflow and the main airflow (main ventilation) in the tunnel creates the phenomenon of injecting cold air into the main flow environment through a nozzle on the air duct. This nozzle can also be understood as a vent (Karagozian, 2014; Szlązak et al., 2018). The interweaving of the two flow fields in the long and narrow tunnel space will create a complex structure for the cooling range (Gopalan et al., 2004; Alabyev et al., 2020). The addition of cold airflow at points along the length of the tunnel can be understood as a unified flow pattern within the main airflow. In previous studies, this solution has not been considered for application in underground coal mines in Vietnam. Therefore, it provides a valuable theoretical basis and ideas for research, offering a new perspective to optimize the design of local cooling systems in underground coal mines.

2. Research Method

Theoretical and empirical analysis methods are used to clarify the cooling capacity at designated points. On that basis, a solution to improve the cooling capacity of the MK-300 air conditioner for the longwalls far from the mine center has been formed. The ability to provide cold airflow to the required points through the air duct installed behind the MK-300 air conditioner has been gradually clarified, based on the need for segmented cooling at each worker's position in the long, narrow, and distant mine tunnels (Figure 1).

Air distribution to ensure safety and a suitable microclimate in the workplace is considered the main objective of controlling the underground thermal environment. Specifically, it aims to increase oxygen concentration, reduce dust concentration, dilute pollutants, and maintain a hygienic working environment. In the confined and high-temperature spaces of underground coal mines, the need for cooling is a primary concern for miners. The ventilation network plays an important role in ensuring the safety of workers' lives and health (Kuyuk et al., 2020; Li and Fu, 2020). Therefore, all tunnels in mine must be provided with an appropriate amount of air to meet this objective. For example, according to the Vietnam Underground Coal Mining Safety Regulations (Ministry of Industry and Trade, 2011), the allowable air velocity range is specified as 0.25÷4 m/s for longwall faces. This range is designed to ensure adequate air supply for a safe working environment. It also confirms that the design and management of mine ventilation and air cooling are key to controlling a safe and efficient underground working environment.

In practice, cooling measures must be taken to adjust environmental parameters when the temperature reaches a specific threshold. According to the Vietnam Underground Coal Mining Safety Regulation (Ministry of Industry and Trade, 2011), operations must stop if the air temperature in the longwall face exceeds 30^{0}C or 34^{0}C in the electromechanical equipment chambers. When the temperature exceeds these limits, cold airflow must be supplemented by mechanical cooling methods. In underground mines, mechanical cooling is often the solution to

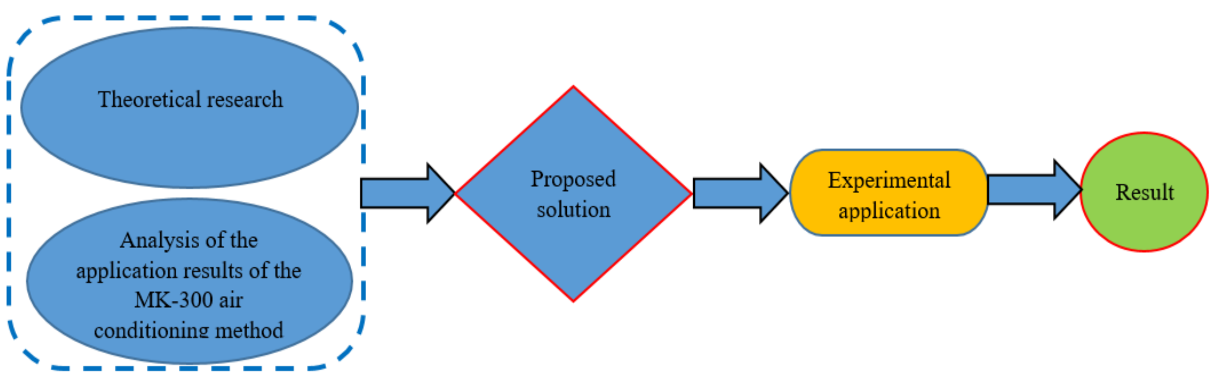

Figure 1. Diagram of research steps.

supplement cold air to the existing tunnel ventilation system. For example, the MK-300 air conditioning method is applied in the Ha Lam and Ha Long coal mines. Although the cold airflow has a low flow rate and can provide local supply to certain locations, the energy consumption of the cooling equipment is significant. Therefore, optimizing cooling solutions is crucial for the production efficiency of underground mines.

With theoretical analysis results, we have applied at the LC-I-9-24B longwall face at level +60/+120 of the Nam Mau coal mine. Although there are no conditions with specialized chillers, the initial results have shown the feasibility of the research solution.

3. Results and discussion

As the mining depth increases in underground coal mines, the geothermal temperature in the mine rock mass also rises. Consequently, the geothermal temperature from the mine rock mass and humidity significantly influences the airflow. Additionally, the heat dissipation of equipment and the heat generated by coal when exposed to oxygen in the gob area contribute to the uneven distribution of temperature and humidity in the mine airflow. If a cooling device is used to inject cold air into the general airflow across the entire cross-section of the tunnel (Figure 2a) (Dao et al., 2017; Dao and Le, 2019; Dao et al., 2019), it will be similar to building air conditioning systems, aiming for dilution. However, this solution does not consider the specific locations of the workers, resulting in a wide cooling effect and a significant cooling capacity requirement. When cold air enters the longwall face, it exchanges heat with surrounding rock, materials, and equipment, leading to rapid heating and insufficient cooling efficiency for remote locations. A significant portion of the cooling capacity in this solution remains unused, resulting in inefficiency. Therefore, improving cooling efficiency and capacity utilization in underground mine environments is still challenging.

The risk of severe thermal shock often occurs at remote and deep longwall locations. Reducing the temperature of the airflow by 3÷5^{0}C is a challenge for underground coal mines in Quang Ninh, Vietnam. Achieving such a significant temperature reduction poses both technical and microclimatic challenges. The significant temperature difference between the main airflow and the surrounding rock near the longwall faces can lead to excessive heat release from the mine rock, necessitating a substantial cold air supply capacity. To address this problem and overcome the limitations of previous solutions, a method involving the supply of cold air at designated

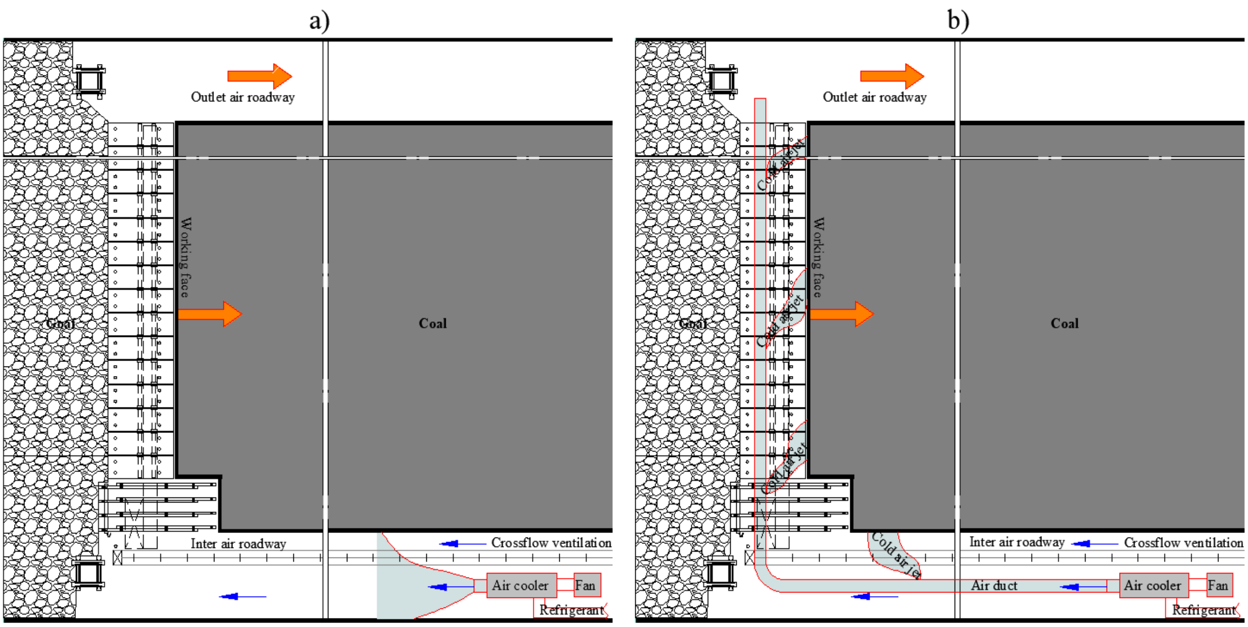

Figure 2. Diagram of cooling solution using the air conditioner in the longwall face area: a) cooling the entire tunnel and longwall face space; b) segmental cooling for each working position of miners.

points along the longwall faces can be applied (Figure 2b). This solution entails providing a cold air duct along the tunnels from the MK-300 air conditioner. At each necessary point, the cold air stream will be sprayed through a nozzle to supplement cooling at each worker's position. This method optimizes cooling efficiency and helps minimize thermal challenges associated with long, deep, and narrow longwalls. It is essentially a fractional cold air supply method that minimizes temperature gradients and prevents problems caused by excessive temperature variations at the miner’s workstation. It allows for precise temperature control at the required locations, thereby enhancing cooling efficiency for workers. It is considered a highly feasible solution for achieving effective temperature reduction in remote longwall faces in deep coal mines.

The segmented cooling mode according to designated points is an air distribution control method based on the concept of heterogeneous environment control for demand-based cooling. In each production shift, miners usually work and move along relatively fixed trajectories. Therefore, by adjusting the targeted cold airflow, a concentrated supply can be provided to the miner's location.

The working characteristics of miners show that the effective cooling zone will be concentrated around their head and neck areas (Figure 3). These areas are most exposed to the surrounding air environment. Consequently, the area around the worker's head and neck along their moving path is identified as the effective cooling zone, while other areas are classified as ineffective cooling zones. Given the space constraints caused by the arrangement of underground equipment, the actual cooling demand of workers is relatively limited. Thus, by accurately adjusting the cold airflow to the cooling zone around their head and neck, the goal of improving the cooling capacity of the air conditioner in underground coal mines can be achieved the cold air stream is sprayed radially from the vent on the air duct into the main air stream in the tunnel. According to the flow regime, the cold air stream spreads and deviates within the trajectory of the main air stream (Figure 3b). The deviated and spread area of the cold air stream will cover the cooling zone around the head and neck of the workers, creating a comfortable environment for them. This demonstrates the feasibility of cooling each designated point through the cold air ducts behind the air conditioner. However, for the cold air stream to reach the locations where the miners need cooling, it is necessary to adjust the parameters of the cold airflow rate and the size of the vent. In this solution, there is a characteristic of two intertwined flows (the cold air stream

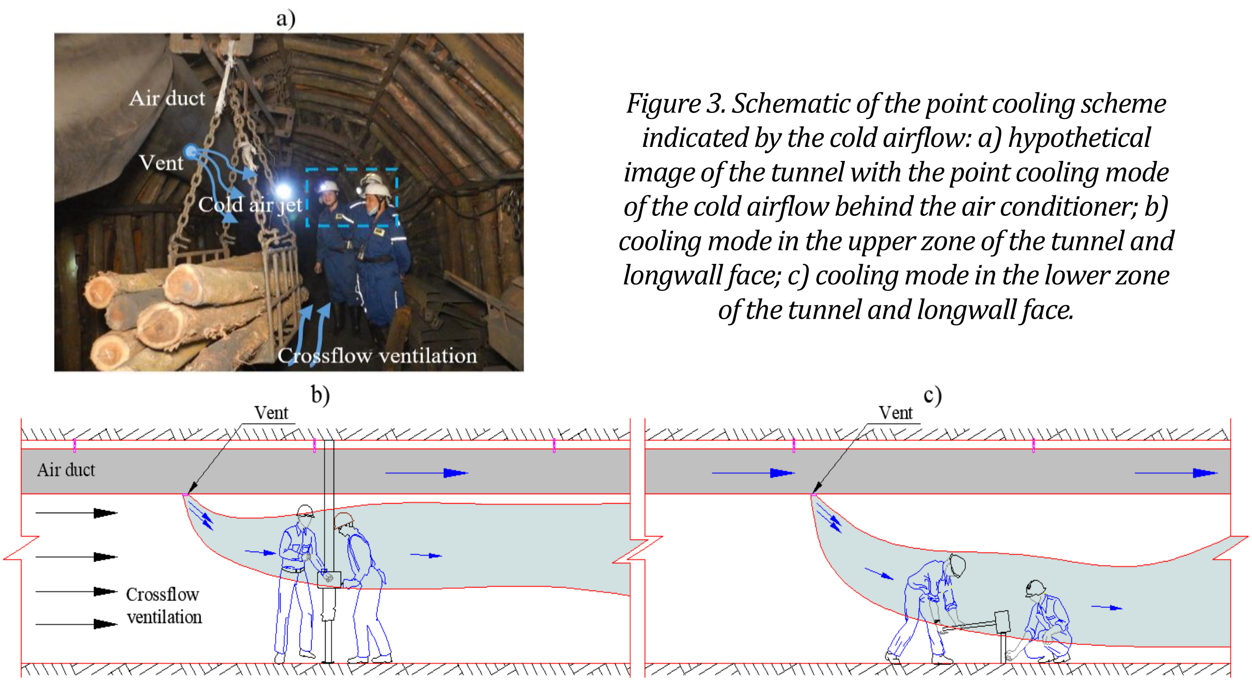

Figure 3. Schematic of the point cooling scheme indicated by the cold airflow: a) hypothetical image of the tunnel with the point cooling mode of the cold airflow behind the air conditioner; b) cooling mode in the upper zone of the tunnel and longwall face; c) cooling mode in the lower zone of the tunnel and longwall face.

intertwines with the main airstream). This leads to the formation of a cross-directional microclimate zone at each specific section of the cooling point (Figure 4).

As shown in Figure 4a, the cold airflow will be deflected due to the influence of the main airflow. The deflection of the airflow results from the interweaving of the two streams and the passage in the tunnel with limited space. Moreover, a specific airflow velocity is always specified in the tunnels; for example, in the longwall face, it is 0.25÷4 m/s.

When the velocity of the cold airflow is lower than that of the main airflow (Figure 4b), a large deflection angle of the air stream will be formed. The outer boundary mixes with the main air stream, while the upper boundary is limited by the upper wall of the tunnel. The specific flow field can be divided into the following regions: I - the low-velocity region of the cold airflow after exiting the air duct, with a relatively short distribution length; II - the region of the cold airflow with a large turning angle, which is completely squeezed by the main airflow, resulting in most of the cooling zone adhering to the upper wall of the tunnel; III - the cold airflow completely adheres to the upper wall of the tunnel, with the outer boundary continuously mixing with the main airflow. The analysis results of this diagram show that the velocity of the cold airflow is smaller than that of the main airflow, leading to the cooling zone occurring only on the upper wall of the tunnel.

When the cold airflow gradually increases in velocity and exceeds that of the main airflow, the deflection angle of the cold airflow gradually decreases after exiting the air duct, while its obstruction effect on the main airflow increases (Figure 4a). This changing feature develops from the upper wall-adhering airflow to the tunnel's center, dividing the main airflow into a low-velocity zone and a high-velocity zone. The low-velocity zone, mainly formed by the surrounding airflow after the main flow is obstructed, is located between the inner boundary of the cold airflow and the upper wall. Additionally, the low-velocity zone is situated between the lower boundary of the cold airflow and the lower wall due to the compression of the main flow. Therefore, the mixing of the cold airflow and the main airflow mainly occurs at their upper and lower boundaries. The specific flow field can be divided into regions I, II, and III. Zone I is the initial region of the cold airflow after exiting the air duct, characterized by a strong airflow core. The deviation angle of the cold airflow in this zone is relatively small, consistent with the designated exit direction of the cold airflow. In Zone II, changes start from the end of Zone I, and the direction gradually becomes parallel to the main flow. The deviation of the cold airflow trajectory in this zone is influenced by the pressure gradient in the diagonal direction, causing the flow velocity to decrease more rapidly. The resistance of the main flow is more pronounced than that in Zone I but does not cause the cold airflow to adhere to the upper wall of the tunnel. In Zone III, the

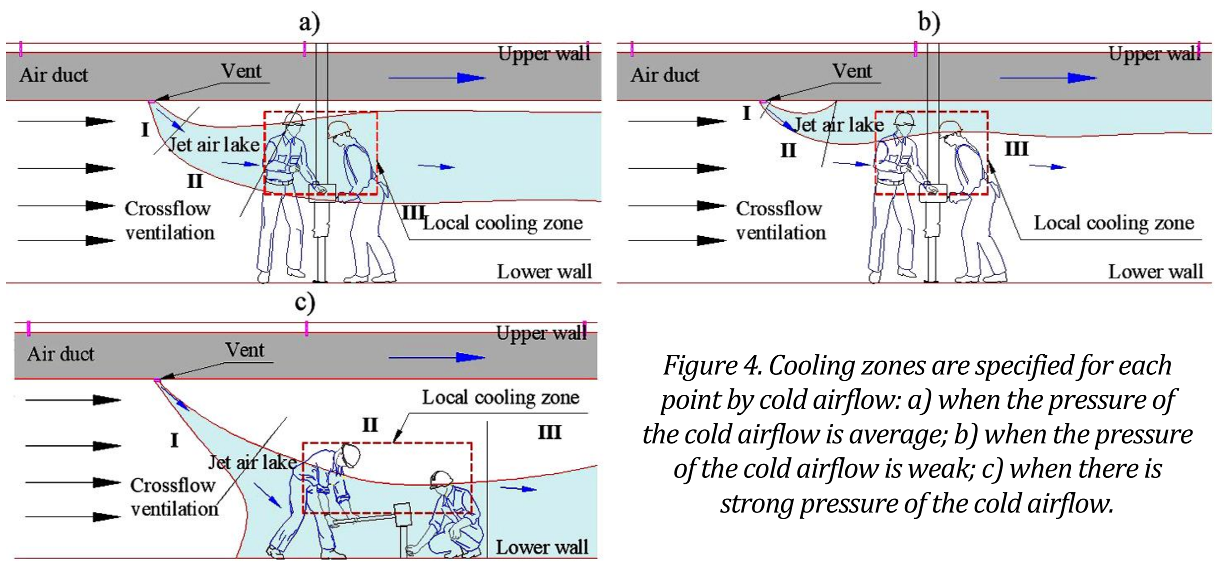

Figure 4. Cooling zones are specified for each point by cold airflow: a) when the pressure of the cold airflow is average; b) when the pressure of the cold airflow is weak; c) when there is strong pressure of the cold airflow.

direction of the cold airflow is parallel to that of the main airflow. The cold airflow and the main airflow in the confined space are in a parallel flow state. The mixing of the two airflows leads to the gradual convergence of the cold airflow velocity to that of the main airflow, ultimately resulting in the weakening and disappearance of the cold airflow.

When the velocity of the cold airflow increases to a certain level, the lower wall becomes the boundary of its deflection. This leads to the rapid collision of the cold airflow with the lower wall, forming a collision flow (Figure 4c). Unlike Figure 4b, the cold airflow is not affected by the main airflow and remains almost unchanged after exiting the duct. The specific flow field in this case is also divided into regions I, II, and III. In zone I, the cold airflow is longer due to its high velocity, where it is not directly affected by the furnace wall or the main airflow. In zone II, the cold airflow is completely confined by the lower wall, creating a stagnation point. Due to the high airflow velocity and pressure at the collision point, the cold airflow is diverted to one side and adheres to the lower wall, with the pressure gradually returning to the same level as the main airflow. In zone III, the cold airflow adheres to the lower wall and encounters resistance from the main airflow, causing it to gradually adjust and blend into the main airflow.

The distribution of cold airflow according to points in the tunnel, focusing on providing effective cooling for workers, is shown in Figure 5. Based on the above analysis, the effectiveness of the solution is determined by its main parameters, including effective cooling height (H_e), ineffective cooling height (H_u and H_l), size of the cooling zone (D_e), and non-cooling zones (D_u and D_l). The relationship of these parameters can be expressed by equation (1) (Wang et al., 2024):

$$(D_u + D_e + D_l) = (H_u + H_e + H_l) \quad (1)$$

The main objective of the point-based cold air distribution is to ensure that D_e fully covers H_e while maintaining $D_u \le H_u$, $D_e \ge H_e$, and $D_l \le H_l$ along the miner's body movement trajectory. Designing the cold airflow in this way will provide sufficient cooling for the miner while still effectively utilizing the main airflow in the tunnel.

In the case where the tunnel height is close to the sum of H_e and H_l, the "Low Mode" with a low-velocity cold airflow can be used for local cooling (Figure 5b). This scenario occurs when $D_u = 0$, which causes the main control condition to be mostly located at the top of the tunnel. When the tunnel height is larger than the sum of H_e and H_l, the "Mid Mode" (Figure 5a) is used, in which the upper boundary of the cold airflow separates from the upper wall to form a deflected airflow. This case can meet the control requirements of the cooling zone at the miner's head and neck. Under this condition, $H_u > 0$ and $D_u > 0$, and a cooling zone is formed in the middle of the tunnel. When the worker works in the lower space of the tunnel (Figure 5c), a high-velocity cold airflow is required. This will result in the main cooling zone near the lower wall. However, in this cooling mode, a high pressure will be required to push the cold air stream downward. This may result in

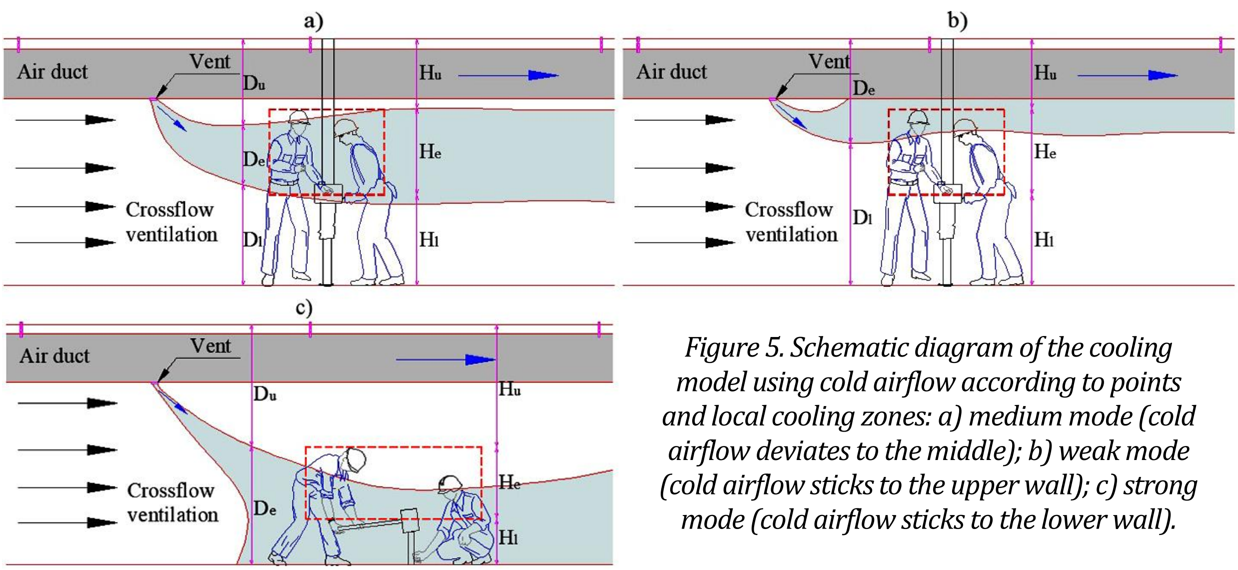

Figure 5. Schematic diagram of the cooling model using cold airflow according to points and local cooling zones: a) medium mode (cold airflow deviates to the middle); b) weak mode (cold airflow sticks to the upper wall); c) strong mode (cold airflow sticks to the lower wall).

more wasted cooling capacity than in the above two cases. Moreover, the cooling area of the cold air stream with a higher velocity may reduce human comfort. Therefore, the effectiveness of the cold air stream cooling mode as an effective air distribution method for local cooling in the confined space of underground coal mines needs to be further considered in specific cases.

When miners are located far apart, the cooling effect of a single cold airflow is often insufficient. The reason is that after being discharged from the air duct, the diffusion width of the cold airflow expands. At a certain distance, the cold airflow slows down and mixes with the main airflow. At that point, the temperature of the cold airflow may not be sufficient to meet the cooling requirements for a large volume, so it becomes necessary to deploy cold airflow nozzles at multiple points. By using cold air stream nozzles at multiple points, the ability to reduce temperature can be achieved for various work positions. The distance between the cold airflow nozzles depends on each worker's position and must ensure sufficient velocity and cold temperature for effective cooling.

Case study: Currently, the MK-300 air conditioners are in the phase of stopping operation at Ha Lam and Ha Long coal mines. Therefore, testing the cold airflow from the MK-300 is not feasible. To test the effectiveness of the proposed solution, we chose to test the spraying of airflow taken from the air compressor. The applied location is at the LC-I-9-24B longwall face at level +60/+120 of the Nam Mau coal mine. The airflow is taken from the drilling machine of the workers in the longwall face. The wind speed in the longwall is measured at 1.4 m/s, with a temperature of 30.1^{0}C. The nozzle has a diameter of 19 mm, the temperature of the airflow after leaving the nozzle is 27^{0}C and the speed is 8.3 m/s (Center for Mining Science and Technology & Environment, 2023). The summary of the test results is shown in Figure 6.

Figure 6 shows that after the airflow was injected into the longwall face, at a distance of 1.5 m and after 5 minutes, the measured temperature was 29^{0}C. This represents a reduction of the initial temperature by 1.1^{0}C. At distances of 5 m and 8 m, the temperature gradually increased to 29.6^{0}C and 29.8^{0}C, respectively. Thus, the cooling range

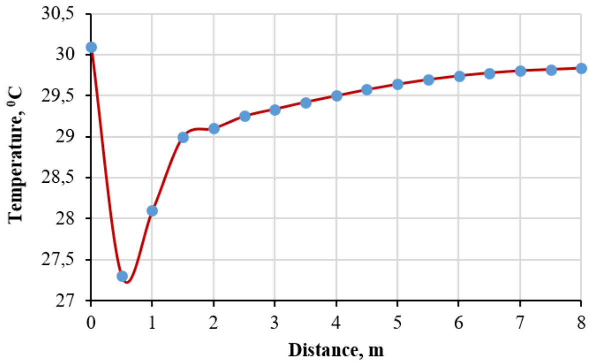

Figure 6. The temperature of the airflow after exiting the air nozzle in the LC-I-9-24B longwall face.

is not wide but is sufficient to surround the worker's working position, contributing to a reduction in temperature and creating a comfortable environment for the miner. This is the case when using airflow with a temperature of 27^{0}C. If a cold air stream of 20÷22^{0}C from the MK-300 air conditioner is used, the cooling efficiency will increase significantly.

4. Conclusions

This paper considers improvements in the ability to reduce temperature in the longwall face when using air conditioning in underground coal mines in Vietnam. This also aligns with the goal of controlling the thermal environment in underground spaces, particularly in remote and deep longwall faces and tunnel areas of underground coal mines. Some main conclusions of the paper are as follows:

- A local cooling solution using cold airflow at designated points has been proposed and discussed. The core of this solution is to effectively utilize the cooling capacity by directing cold airflow from the air conditioner to the required locations using ducts. This will serve as the basis for distributing cold airflow at each nozzle suitable for the workplace.

- The results of the case study show that the proposed solution can reduce the temperature at the worker's work location by 1-2^{0}C. However, this is a preliminary study. If a cold air stream of 20÷22^{0}C from the MK-300 air conditioner is used, the cooling efficiency will increase significantly.

This study provides valuable insights into the characteristics of airflow and the efficiency of local cooling at designated points. However, it does not consider the thermal effects of equipment, rock, and coal. A direct evaluation of cooling efficiency in the field has not been carried out. Nonetheless, this paper serves as a foundation for future research on practical.

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Contributions of authors

Phuc Quang Le - conceptualization, methodology, model and simulation, writing - original draft, review & editing; Tien Trung Vu - data analysis and editing; Chi Van Dao - data analysis; Cuong Hong Nguyen - review & editing, supervision.

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