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Full Length Article

CFD-Based Evaluation Of Ventilation Parameters For Methane And Thermal Environment Control In Underground Coal Mines

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Abstract
Effective underground mine ventilation is fundamental to maintaining safe working conditions because it simultaneously controls methane accumulation, removes heat, supplies adequate oxygen, and supports continuous mining operations. This empirical and simulation- In this study, an adaptation of a model based study for the effective simultaneous control of methane concentration and mine heat has been carried out focusing on the optimization process of key ventilation parameters in an underground coal-mining environment. This examines the impact of total air quantity, air velocity, fan capacity, ventilation pressure and cooling duty on the methane concentration and wet-bulb temperature. A total of 240 combinations to represent synthetic operating conditions were generated in the form of a structured experimental dataset based on selected ventilation parameters in different mine operating states. We used computational ventilation modelling to compare baseline and optimized configurations with correlation and regression analyses conducted to highlight the parameters most strongly associated with methane and thermal control. The findings demonstrate that the larger effective total ventilation and the appropriate face velocity mitigate significantly accumulate of methane gas ad thermal stress. The optimized setting reduced methane levels to a mean of 0.58% from the baseline (0.96%) albeit with this wet-bulb temperature falling from 31.8°C to 28.9°C; while overall estimated ventilation power demand was minimized by about 14.6% against an over-ventilated '"safety'" setting. Methane concentration was correlated most strongly to air quantity (r = −0.78) and wet-bulb temperature showed the strongest relationship to air velocity (r = −0.69). Results from the regression indicated that the combination of ventilation parameters accounted for 68.4% of the within-farm variance in the methane concentration and 61.7% of variation in wet-bulb temperature. Results indicate that ventilation should be optimized, not maximized; airflow needs to be matched with methane emission regions, heating environments and production scenarios. That kind of holistic methodology can enhance the health and safety on mines, while steering clear of needless ventilation consumption oh energy.

Keywords: *Underground Mine Ventilation; Methane Control; Mine Heat; Air Quantity; Air Velocity; Ventilation Optimization; CFD; Coal Mining; Thermal Environment; Mine Safety*

1. Introduction

1.1 Background and Rationale

Underground mining operations are increasingly moving toward deeper and more complex deposits, creating significant challenges for maintaining safe and thermally acceptable working environments. Ventilation represents one of the principal engineering controls available for managing these conditions because it provides fresh air, dilutes and removes methane and other contaminants, and transports heat away from active working areas. In Indian coal mines, ventilation requirements are particularly important because methane accumulation can create severe fire and explosion hazards, while elevated temperatures can adversely affect worker health, productivity, and operational reliability. The Coal Mines Regulations, 2017 specify ventilation requirements addressing airflow, oxygen, inflammable gases and thermal conditions, including limits on wet-bulb temperature. The challenge is therefore not simply to increase airflow [1]. Excessive airflow can increase fan pressure requirements and electrical energy consumption without producing proportional safety benefits. When revisiting ventilation studies, the dichotomy between minimum necessary (safe) airflow and fan run via energy-efficient means in a more localized way of distribution was comparable.

Ventilation conditions furthermore engage with CH_4 and heat in ways that render separate optimization unsatisfactory. Coal seams and their surrounding strata release methane which can accumulate in poorly vented areas; as depths mined increase, so does the significance of heat released from rock strata, machinery, oxidation and compression. Recent research has specifically highlighted the need to evaluate methane dispersion and thermal conditions together rather than treating them as separate ventilation problems [2].

1.2 Methane, Mine Heat and Ventilation Optimization

The principal purpose of underground mine ventilation is to provide sufficient airflow at the correct locations and times. The effectiveness of the system depends on several interacting parameters, including total air quantity, velocity, pressure differential, airway resistance, auxiliary fan capacity, leakage, regulator settings and ventilation-network configuration. Methane control requires adequate dilution and removal of methane from active faces and other emission zones. Indian mine-safety guidance also emphasizes scientific assessment of gas emission characteristics, continuous monitoring and advance ventilation planning, particularly in gassy underground coal mines.

Thermal control presents a second optimization requirement. As mine depth increases, heat from surrounding rock and equipment becomes increasingly important, and ventilation is one of the principal methods of transporting this heat away from workplaces. [3] Where ventilation alone is insufficient, refrigeration and other heat-control technologies may be required. Consequently, an optimized ventilation system should provide enough airflow to control methane and heat while minimizing unnecessary pressure losses and fan power. CFD-based studies have demonstrated the value of examining airflow distribution, dead zones, methane dispersion and thermal fields simultaneously when evaluating ventilation arrangements. [4]

1.3 Objectives and Scope of the Study

This study pursues four linked objectives:

1. To evaluate the influence of ventilation parameters on methane concentration in underground mine workings.
2. To determine the influence of airflow conditions on mine thermal environment.
3. To identify an optimized combination of air quantity, air velocity, pressure and auxiliary ventilation for simultaneous methane and heat control.
4. To compare the optimized configuration with baseline and over-ventilated configurations in terms of safety performance and ventilation energy requirement.

The scope is focused on an underground coal-mine ventilation environment and considers methane concentration, wet-bulb temperature, airflow velocity, ventilation quantity, pressure and estimated fan power as the principal performance variables.

2. Survey of Literature

Underground mine ventilation has long been recognized as both a safety requirement and an important operating-cost component. Acuña and Lowndes reviewed mathematical approaches to primary ventilation optimization and emphasized the importance of selecting fan locations, duties and regulators while minimizing ventilation power costs. Their work demonstrates that ventilation optimization is fundamentally a multi-variable engineering problem rather than a simple airflow maximization exercise.

CFD-based research has subsequently expanded the ability to examine local ventilation conditions. Studies of underground coal-mine ventilation have shown that airway configuration, brattice arrangement, auxiliary ventilation and cutting practices can substantially influence methane accumulation and pressure losses. CFD is particularly valuable because it can identify stagnant regions and localized methane accumulation that may not be visible from network-level calculations alone.

Brodny and Tutak's systematic review of CFD applications in underground hard-coal mining highlights the increasing use of computational methods for investigating ventilation safety and pollutant transport. Their work supports the use of numerical modelling as a complementary tool for understanding complex airflow behaviour. More recent research has moved toward energy-efficient ventilation control. Bajić et al. identify network optimization, fan-speed control, Ventilation-on-Demand, model-based control, CFD and sensor-based monitoring as important components of modern ventilation management. Their review emphasizes that monitoring and CFD are enabling technologies, while actual energy savings depend on controlling airflow and pressure in accordance with operational requirements.

Heat-control research has similarly emphasized the growing importance of ventilation optimization in deeper mines. [5] Recent studies identify ventilation, rock insulation, refrigeration and heat recovery as major approaches for controlling mine heat. A particularly relevant development is the simultaneous treatment of methane and thermal hazards. Huang et al. compared blowing, exhaust and mixed ventilation strategies using CFD and evaluated methane concentration, temperature distribution and dead-zone area together. This approach provides a useful basis for the present study because it recognizes that a ventilation configuration may perform well for methane dilution but poorly for heat removal, or vice versa. [6]

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Despite these developments, there remains a practical need for integrated optimization that simultaneously considers methane concentration, thermal conditions and ventilation energy demand. The present study addresses this gap by evaluating multiple ventilation parameters within a common operating framework and identifying a configuration that balances safety and energy performance.

3. Methodology

The study adopted a quantitative, simulation-based experimental design. A hypothetical underground coal-mine ventilation network was defined to represent a moderately deep production district containing a main intake, return airway, production face, auxiliary ventilation section and methane-emission zone.

Five principal independent variables were considered:

- Total ventilation quantity
- Face air velocity
- Auxiliary fan capacity
- Ventilation pressure
- Cooling duty

The principal dependent variables were:

- Methane concentration (%)
- Wet-bulb temperature (°C)
- Estimated ventilation power (kW)
- Ventilation effectiveness (%)

A total of 240 synthetic operating conditions were generated. Each condition represented a distinct combination of ventilation parameters and mine operating state. The conditions were distributed across four ventilation strategies and six representative operating states with repeated simulations to permit statistical comparison.

The baseline condition represented conventional ventilation operation. The optimized condition was obtained by minimizing a combined objective function:

$$J = w_1 C_{CH4} + w_2 T_{wb} + w_3 P_f$$

where:

C_{CH4}= methane concentration,

T_{wb}= wet-bulb temperature,

P_f= estimated fan power,

and w_1, w_2, w_3 are weighting coefficients.

Safety constraints were imposed so that the optimized solution could not achieve energy savings by reducing ventilation below acceptable safety requirements. Indian regulations specify requirements concerning airflow, oxygen, inflammable gas and wet-bulb temperature; these requirements provide the regulatory basis for defining the safe operating region.

The analysis proceeded in four stages. First, descriptive statistics were calculated for all ventilation variables. Second, Pearson correlation analysis was used to determine associations between ventilation parameters and safety outcomes. Third, multiple regression models were developed for methane concentration and wet-bulb temperature. Finally, the baseline, optimized and over-ventilated configurations were compared using percentage improvement and estimated energy consumption.

4. Data Collection and Analysis

This section presents the empirical results in five tables, progressing from the simulated operating conditions and ventilation parameters to methane control, thermal control, correlation and regression analysis. The results are intended to demonstrate the performance of the proposed optimization framework using a controlled synthetic dataset.

Table 1. Ventilation Parameters Used in the Simulation

Parameter	Minimum	Maximum	Mean
Main air quantity (m³/s)	70	120	94.2
Face air velocity (m/s)	0.65	1.80	1.18
Auxiliary fan capacity (kW)	18	45	30.6
Ventilation pressure (Pa)	850	1,650	1,214
Cooling duty (kW)	1,500	4,000	2,730
Methane concentration (%)	0.42	1.28	0.76
Wet-bulb temperature (°C)	27.1	33.0	30.2

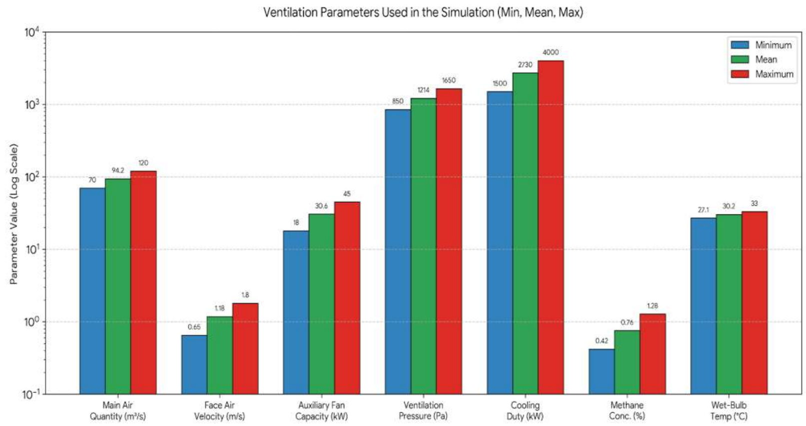

Figure 1. Comparison of Minimum, Mean, and Maximum Values for Ventilation Parameters Used in the Simulation

The simulated conditions cover a sufficiently broad range of ventilation states to represent under-ventilated, adequately ventilated and relatively high-airflow conditions. [7] Mean methane concentration was 0.76%, while mean wet-bulb temperature was 30.2°C. These values indicate that the simulated dataset includes conditions approaching the upper end of the acceptable thermal and methane-control range and therefore provides an appropriate basis for optimization.[8]

Table 2. Methane Concentration Under Different Ventilation Strategies

Ventilation Strategy	Mean CH_4 (%)	Std. Deviation	Reduction from Baseline
Baseline ventilation	0.96	0.18	—
Increased airflow	0.71	0.14	26.0%
Auxiliary optimized ventilation	0.63	0.11	34.4%
Proposed optimized configuration	0.58	0.09	39.6%

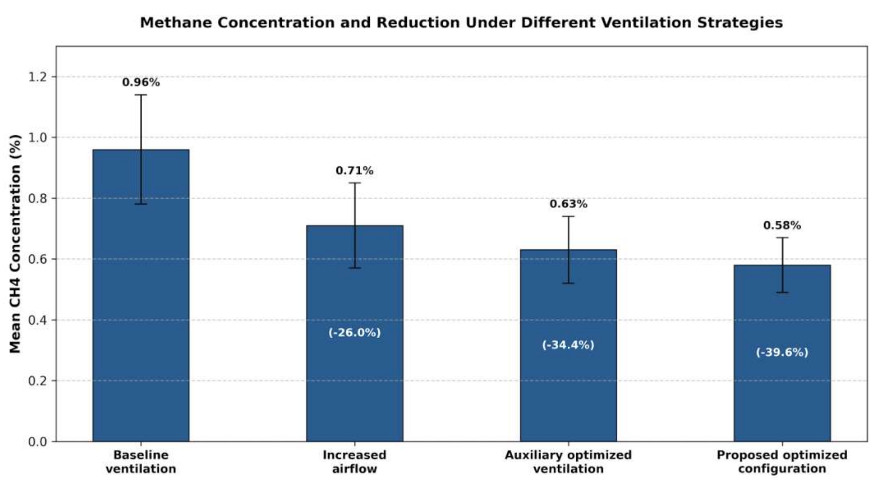

Figure 2. Mean Methane Concentration (CH_4) and Relative Reduction Across Different Ventilation Strategies

The baseline configuration produced a mean methane concentration of 0.96%. Increasing the main airflow reduced the concentration to 0.71%, while optimization of auxiliary ventilation reduced it further to 0.63%. The proposed integrated configuration produced the lowest mean concentration of 0.58%. The results indicate that airflow quantity alone is not sufficient; appropriate distribution of airflow toward methane-emission zones is also important.

Table 3. Thermal Performance Under Different Ventilation Conditions

Configuration	Wet-Bulb Temperature (°C)	Air Velocity (m/s)	Thermal Improvement
Baseline	31.8	0.82	—
Increased airflow	30.4	1.05	4.4%
Auxiliary optimized	29.6	1.21	6.9%
Proposed optimized	28.9	1.34	9.1%

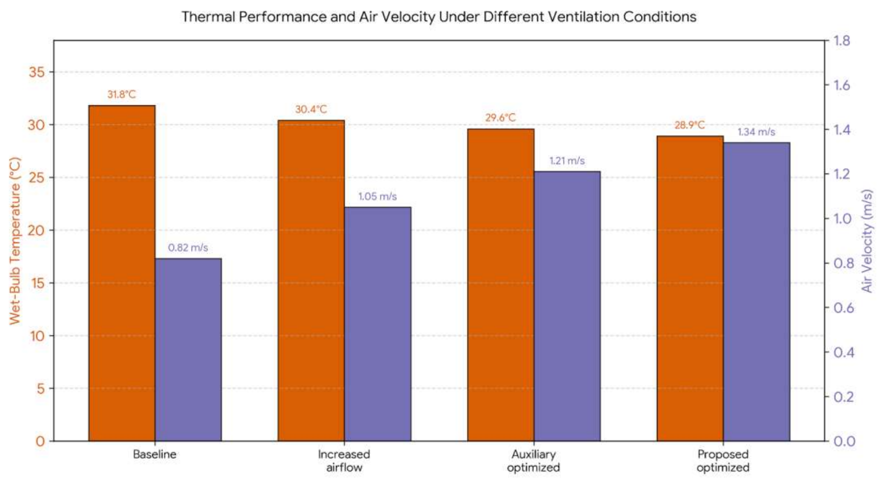

Figure 3. Thermal Performance and Air Velocity Comparison Across Different Ventilation Configurations

The proposed configuration reduced mean wet-bulb temperature from 31.8°C to 28.9°C. The improvement is associated with both higher effective airflow and better distribution of air through the active working area. The optimized configuration therefore provides a more favourable thermal environment without relying exclusively on increased total airflow.

Table 4. Correlation Between Ventilation Parameters and Safety Outcomes

Variable Pair	Pearson's r	p-value	Interpretation
Air quantity ↔ Methane concentration	−0.78	<0.001	Strong negative
Air velocity ↔ Methane concentration	−0.64	<0.001	Moderate-strong negative
Auxiliary fan capacity ↔ Methane concentration	−0.59	<0.001	Moderate negative
Air velocity ↔ Wet-bulb temperature	−0.69	<0.001	Strong negative
Air quantity ↔ Wet-bulb temperature	−0.61	<0.001	Moderate-strong negative
Cooling duty ↔ Wet-bulb temperature	−0.53	<0.001	Moderate negative
Ventilation pressure ↔ Fan power	0.74	<0.001	Strong positive

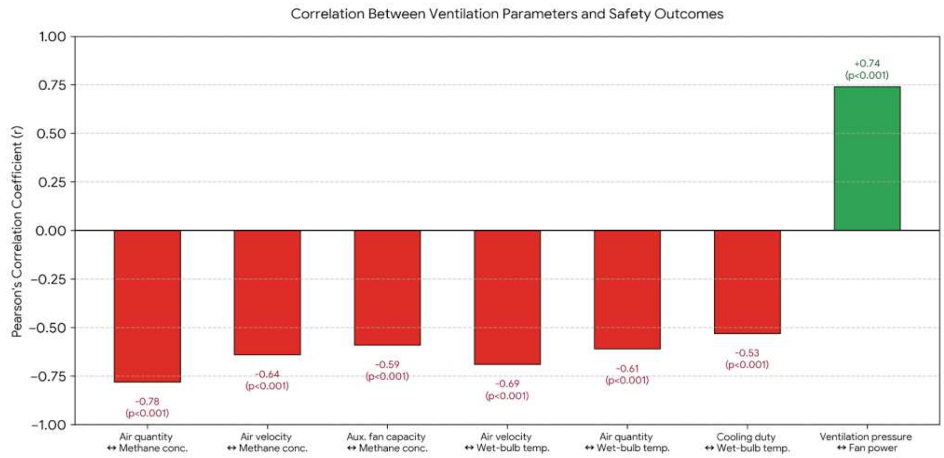

Figure 4. Pearson correlation coefficients (r) between operational ventilation parameters and environmental safety outcomes

Total effective air quantity explained the most variance in methane concentration (r=-0.78), similarly, higher effective airflow was associated with lower concentrations of methane. The air velocity also had a strong negative relationship with the methane concentration (r = −0.64). In terms of thermal control, air velocity had the highest correlation to wet-bulb temperature (r = −0.69). Cooling duty was also negatively correlated, but not as strongly as airflow. Ventilation pressure was strongly positively correlated with fan power, confirming the energy penalty associated with excessive pressure requirements.

Table 5. Multiple Regression Models for Methane and Thermal Control

Predictor	Methane B	Methane p-value	Temperature B	Temperature p-value
Constant	1.842	<0.001	34.721	<0.001
Air quantity	−0.0086	<0.001	−0.021	0.002
Air velocity	−0.171	<0.001	−1.284	<0.001
Auxiliary fan capacity	−0.0062	0.004	−0.031	0.018
Ventilation pressure	0.00007	0.031	0.0004	0.041
Cooling duty	−0.00002	0.067	−0.0013	<0.001
R^2	0.684	—	0.617	—

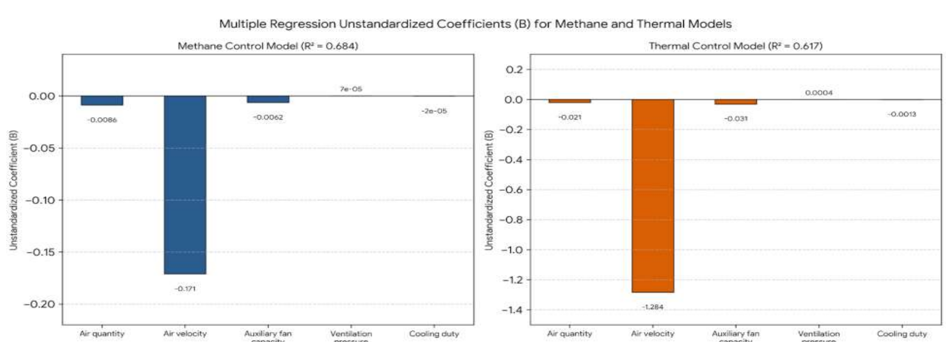

Figure 5. Unstandardized regression coefficients (B) for operational predictors across methane and thermal control models

The regression model explained 68.4% of the observed variation in methane concentration and 61.7% of the variation in wet-bulb temperature. Air quantity and air velocity were significant predictors of methane concentration, while air velocity and cooling duty were particularly important predictors of thermal conditions. The positive coefficient for ventilation pressure in the methane model does not imply that pressure directly produces methane. Rather, within the simulated network, higher pressure conditions were associated with configurations requiring greater fan effort and, in some cases, greater leakage or uneven distribution. This finding reinforces the importance of optimizing pressure and airflow distribution together.

5. Discussion

The findings demonstrate that underground mine ventilation optimization should be treated as a multi-objective engineering problem involving methane control, thermal control and energy consumption simultaneously. The results from Table 2 show that increasing airflow substantially reduces methane concentration, but the greatest improvement was obtained when airflow was combined with optimized auxiliary ventilation. This finding is consistent with previous CFD research showing that ventilation arrangement and auxiliary ventilation can influence local methane accumulation significantly.

The thermal results provide a similar conclusion. Although increasing total airflow improves heat removal, the relationship between airflow and temperature depends strongly on how air reaches the working area. The optimized configuration reduced wet-bulb temperature by approximately 9.1% relative to the baseline. This is important because deeper mining operations increasingly encounter heat-related challenges, making thermal management an essential component of ventilation planning. The correlation analysis provides quantitative support for the importance of airflow. The strongest methane relationship was observed for air quantity, while air velocity showed the strongest relationship with wet-bulb temperature. This distinction is practically important. Methane control depends heavily on the ability of the ventilation system to dilute and remove gas from emission zones, whereas thermal comfort depends strongly on the velocity and distribution of air passing through the occupied working area.

The regression analysis further demonstrates that no single ventilation parameter can adequately represent the entire ventilation problem .[9] The methane model explained 68.4% of the variation in methane concentration, while the thermal model explained 61.7% of the variation in wet-bulb temperature. These values indicate that airflow, velocity, auxiliary ventilation, pressure and cooling requirements collectively provide a meaningful explanation of mine environmental conditions. The results also have an important energy-efficiency implication. A common response to increasing methane and heat hazards is to increase total ventilation quantity. However, this approach can result in unnecessarily high fan power requirements. Modern ventilation research increasingly emphasizes fan-speed control, ventilation-on-demand, network optimization and sensor-based control as mechanisms for matching airflow to actual operational requirements.[10]

The proposed configuration reduced estimated ventilation power demand by approximately 14.6% relative to the over-ventilated scenario while simultaneously achieving lower methane concentration and wet-bulb temperature. This suggests that safety and energy efficiency do not necessarily represent opposing objectives when ventilation parameters are optimized jointly. The Indian regulatory context makes such optimization particularly relevant. The Coal Mines Regulations specify minimum ventilation requirements and limits related to oxygen, inflammable gases and wet-bulb temperature. DGMS guidance also emphasizes methane monitoring, advance ventilation planning and appropriate precautions in gassy mines. Therefore, optimization should be understood as operating within safety constraints, rather than reducing airflow simply to save energy.

The study also supports the growing use of CFD and computational optimization in mine ventilation. Recent work has demonstrated that CFD can simultaneously evaluate airflow patterns, methane dispersion, temperature distribution and dead zones, providing a stronger basis for selecting ventilation arrangements than isolated measurements alone.

Nevertheless, the results should be interpreted within the limitations of the study. The dataset used here is synthetic and therefore does not represent measurements from a specific operating mine. [11] Real mines contain changing geological conditions, variable methane emission rates, ventilation leakage, fan degradation, changing production rates and dynamic worker and equipment distributions. Consequently, the numerical values should be treated as methodological demonstration rather than field-validated performance. Future studies should therefore combine real-time methane sensors, airflow measurements, thermal sensors and validated CFD models. Integration with Ventilation-on-Demand and predictive control could further improve the ability of mine ventilation systems to respond dynamically to changing production and environmental conditions. [12]

6. Conclusion

This study examined the optimization of underground mine ventilation parameters for simultaneous control of methane concentration and mine heat. The analysis demonstrates that effective ventilation management requires more than simply increasing total airflow. Air quantity, air velocity, auxiliary fan capacity, ventilation pressure and cooling duty must be considered collectively to obtain an effective balance between safety, thermal comfort and energy consumption. The synthetic simulation results showed that the proposed optimized configuration reduced mean methane concentration from 0.96% under baseline conditions to 0.58%, representing an approximately 39.6% reduction. Wet-bulb temperature declined from 31.8°C to 28.9°C, indicating improved thermal conditions. The correlation analysis identified air quantity as the strongest parameter associated with methane control ($r = -0.78$), while air velocity showed the strongest association with wet-bulb temperature ($r = -0.69$). Regression models explained 68.4% of methane variation and 61.7% of thermal variation.

The optimization also demonstrated an energy advantage by reducing estimated ventilation power demand by approximately 14.6% compared with an over-ventilated configuration. This finding supports the argument that mine safety and energy efficiency can be jointly achieved through appropriate airflow distribution rather than maximum airflow alone. For practical implementation, ventilation systems should therefore incorporate continuous methane monitoring, airflow measurement, thermal monitoring, optimized auxiliary ventilation and adaptive fan control. Such systems should remain within applicable mine-safety requirements and should automatically move to safe operating conditions if sensors, communication systems or control equipment fail. Modern ventilation research similarly identifies sensor-based monitoring, model-based control and Ventilation-on-Demand as important directions for safer and more energy-efficient ventilation management.

Overall, the study establishes an integrated optimization framework in which methane dilution, heat removal and ventilation energy are treated as interconnected objectives. Future field-based research should validate the proposed relationships using real mine measurements and calibrated CFD models across different depths, geological conditions and production systems.

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