



INFLUENCE OF AIRFLOW RATE AND RELATIVE HUMIDITY ON THE THERMAL EFFICIENCY AND ENERGY CONSUMPTION OF UNDERGROUND MINE VENTILATION SYSTEMS

Maria-Isabela CAȘOTĂ^{1*}, Dan Codruț PETRILEAN²

¹ University of Petroșani, Petroșani, Romania, e-mail: ghicajanumaria@gmail.com

² University of Petroșani, Petroșani, Romania, e-mail: danpetrilean@upet.ro

DOI: 10.2478/minrv-2026-0056

received – 31.08.2026 / revised – 04.09.2026

accepted – 15.09.2026 / published – 25.09.2026

Abstract: *Underground mine ventilation is simultaneously a safety-critical service and a major electrical load. This study evaluates the influence of airflow rate and relative humidity on the thermal and energetic performance of an underground ventilation system using a transparent simulation-based dataset of 90 operating scenarios. Airflow rate varied from 8 to 26 m³/s, relative humidity from 45% to 90%, inlet air temperature from 24°C to 34°C, and pressure drop from 650 to 1550 Pa. Fan electrical power was calculated from airflow, pressure drop and fan efficiency, while thermal effectiveness and a non-regulatory heat-stress proxy were represented through physically motivated response functions. Descriptive statistics, Pearson correlation, multiple linear regression and one-way ANOVA were applied. The analysis illustrates the central energy–thermal trade-off: increasing airflow improves the simulated thermal response but increases fan power, while higher humidity degrades thermal conditions. The framework is intended for methodological screening and subsequent validation with measured mine data.*

Keywords: *underground mine ventilation; airflow rate; relative humidity; fan power; thermal effectiveness; energy efficiency.*

1. Introduction

Underground mine ventilation is one of the few engineering systems whose operation is simultaneously continuous, energy-intensive and directly connected to occupational safety. Its primary function is to provide sufficient fresh air to active workings, dilute gases and airborne contaminants, remove heat and moisture, and maintain environmental conditions compatible with personnel and equipment [1]. These functions become progressively more difficult as mining advances to greater depths. The natural increase in virgin rock temperature, together with heat released by machinery, electrical installations, water inflow and human activity, raises the thermal load that must ultimately be carried away by the ventilation air. In hot and humid workings, the problem is not adequately described by dry-bulb temperature alone: moisture changes the enthalpy of the air and can substantially alter both heat transport and the physiological response of workers. Field measurements in underground tunnelling have shown that the evolution of airflow temperature, humidity and enthalpy along a development heading can be used to identify zones in which heat and moisture are added to the ventilation stream [2].

The energetic consequence of maintaining this environmental control is considerable. Main and auxiliary fans often operate for long periods and must overcome the cumulative aerodynamic resistance of shafts, galleries, bends, doors, regulators and other network components. Consequently, the electrical demand of ventilation is governed not only by the amount of air required underground, but also by the pressure at which that air must be delivered and by the efficiency of the fan–motor assembly. De Souza [3] reported that mine ventilation can represent a substantial share of total mine energy use and showed that avoidable losses in fan installations may consume a meaningful fraction of the input power. From an operational perspective, this means that simply reducing airflow is not the only, and often not the safest, route to energy savings. Reducing

* Corresponding author: Maria-Isabela Cașotă, University of Petroșani, Petroșani, Romania, e-mail: ghicajanumaria@gmail.com

unnecessary resistance, selecting an appropriate operating point and matching air delivery to actual demand can lower energy consumption while preserving the ventilation function.

Airflow rate and relative humidity are particularly useful variables for examining the link between energy demand and underground thermal conditions. Increasing airflow generally improves contaminant dilution and increases the capacity of the air stream to transport sensible heat, but it also increases the work required from the fan. Relative humidity has a different role: it does not directly create fan power demand, yet it changes the psychrometric state of the air, contributes to latent heat content and reduces the potential for evaporative heat loss from the human body. The two variables should therefore not be treated as interchangeable indicators of ventilation quality. The present study examines them together with inlet temperature and pressure drop in a controlled simulation framework. The intention is not to reproduce a particular mine, but to establish a transparent engineering baseline in which the principal energy–thermal relationships can be quantified and later replaced or calibrated with field measurements.

2. Literature Review

2.1 Underground Mine Ventilation as an Energy and Safety System

Mine ventilation has a dual objective: it must satisfy non-negotiable safety requirements while using energy efficiently. Classical ventilation engineering describes airflow distribution through interconnected branches whose resistances determine the pressure required from the fan [1]. In practice, the energetic performance of the system depends not only on the nominal efficiency of the fan but also on leakage, abrupt transitions, poorly designed fan stations, regulators and the location of resistance within the network. De Souza showed that redesigning fan assemblage components can markedly improve overall installation efficiency and reduce the base electrical load of a mine [3].

This distinction between fan efficiency and ventilation-system efficiency is important. A fan can operate near an acceptable point on its characteristic curve while the overall system remains inefficient because a large pressure rise is consumed by avoidable losses. Contemporary reviews of underground ventilation control consequently emphasize three complementary intervention levels: reduction of network resistance, adjustment of fan operating points, and temporal or spatial matching of airflow to actual demand [4]. The implication for the present study is that airflow rate cannot be interpreted as an isolated performance indicator; it must be considered together with pressure drop and fan efficiency.

The practical difficulty is that the required airflow is not constant in space or time. Production areas move, equipment fleets change, blasting and re-entry create temporary demands, and some branches of a network may be inactive during parts of a shift. Historically, many installations have nevertheless been operated close to a conservative maximum condition because fixed-speed operation is simple and robust. This approach provides a safety margin but can also maintain high electrical demand when the full design quantity is not required. Ventilation-on-demand strategies address this mismatch by adjusting fan operation or airflow distribution according to production and environmental requirements [5, 6]. Their usefulness, however, depends on reliable sensing and on maintaining minimum safety constraints throughout the network; energy efficiency cannot be considered independently of the ventilation duty.

2.2 Thermodynamic Basis of Heat Transfer in Underground Workings

The thermal state of underground air results from coupled sensible and latent heat transfer. Conduction through the rock mass, convection at the rock–air interface, heat released by machinery and electrical equipment, human metabolic heat, water inflow and evaporation all contribute to the local energy balance. The general heat-transfer principles of conduction, convection and radiation, together with energy-balance formulation, provide the physical basis for evaluating these exchanges [7]. Petrilean’s work on real heat balances for thermal equipment illustrates the broader engineering principle that useful energy transfer and losses should be quantified through an explicit balance rather than inferred from a single operating variable [8]. Although the steam-generator application differs from mine ventilation, the balance methodology is relevant to the organization of thermal inputs, outputs and losses.

In mine airways, the ventilation stream acts as the transport medium that removes part of the heat released to the underground environment. Field measurements by Chu et al. demonstrated that thermodynamic airflow parameters can be used to identify heat and moisture sources along a hot and humid development tunnel [2]. The temperature response therefore depends on both the magnitude of the heat sources and the mass flow of ventilation air available to absorb that heat. This is why deeper mines frequently require a combined strategy of ventilation, refrigeration and local heat-source management rather than a single control measure.

A useful way to interpret the underground heat balance is to distinguish between heat generation, heat transfer to the air and heat transport by the air. A local source may increase wall or equipment temperature without immediately producing the same increase in air temperature; the final response depends on convective coefficients, exposed area, duration and the mass flow of air. Moisture introduces a second transport mechanism because evaporation adds latent heat to the ventilation stream. For this reason, two air states with the same dry-bulb temperature can represent different thermal loads when their humidity ratios differ. The heat-transfer framework described by Petrilean [7], together with balance-based analyses of real thermal systems [8], is useful in this context because it emphasizes conservation of energy rather than relying on temperature as an isolated performance indicator.

2.3 Airflow Rate, Pressure Loss and Fan Power

The mechanical energy required to move air through a mine is determined by volumetric airflow and the pressure rise supplied by the fan. In simplified form, fan electrical power may be expressed as $P = Q\Delta p/\eta$, where Q is airflow rate, Δp is fan pressure rise and η is the overall fan–motor efficiency. Mine resistance causes pressure demand to increase rapidly as airflow is increased, so apparently modest increases in required air quantity can produce disproportionately large increases in power consumption. This relationship is one of the principal reasons why oversupplying air is energetically expensive [1, 3].

Petrilean's studies of helical screw compressors are not mine-fan studies, but they provide a useful parallel in the analysis of mechanical systems that convert electrical input into pressure-related fluid work. The monograph on helical screw compressors discusses compressor construction and energetic operation [9], while the mathematical method proposed for determining compressor power input formalizes the relationship between thermodynamic state, compression process and absorbed power [10]. A separate analysis of energy losses through a screw-compressor casing further emphasizes that component-level losses must be included when evaluating real energetic performance [11]. In the present paper these works are used as methodological thermodynamic references rather than as direct evidence for mine-fan behavior.

For mine ventilation specifically, the practical consequence is that energy optimization must address both sides of the power relation: the required airflow and the pressure needed to deliver it. Network modifications that reduce resistance can lower power without reducing useful airflow, whereas airflow reduction can only be considered where contaminant, thermal and statutory constraints remain satisfied. This distinction is essential when interpreting specific ventilation energy and when comparing operating scenarios.

The pressure requirement of a real ventilation network is also distributed rather than concentrated at a single location. Friction along airways, local losses at changes of section and direction, regulators and leakage all contribute to the total pressure that the fan must supply. This has an important operational implication: two networks delivering the same useful airflow can have markedly different electrical demands if one contains larger avoidable losses. The distinction is analogous to other fluid-machinery systems in which absorbed power reflects both useful fluid work and internal or installation losses. Petrilean's work on screw compressors [9, 10, 11] is relevant at this methodological level, even though compressors and mine fans operate in different pressure regimes, because it illustrates the value of separating useful thermodynamic work from the losses that determine actual input power.

2.4 Influence of Airflow on Underground Thermal Conditions

Airflow rate directly affects the capacity of the ventilation stream to transport sensible heat. For a given thermal load, increasing the mass flow of air reduces the temperature rise required to carry the same sensible heat. In deep mines, this relationship is complicated by heat exchange with surrounding rock, changing airway geometry, equipment loads and moisture sources. Nevertheless, airflow remains one of the most accessible operational variables for modifying local thermal conditions.

Nie et al. investigated heat treatment and ventilation optimization in a deep mine and demonstrated the need to coordinate cooling measures with ventilation design [12]. Dosa et al. likewise showed that the efficiency of underground spot cooling depends on the ambient conditions at the point of use [13]. More recently, Ihsan et al. developed a hybrid method for analyzing underground air thermal conditions and predicting Wet Bulb Globe Temperature, illustrating the growing use of combined physical and data-driven models for heat assessment [14]. Together these studies support the inclusion of airflow as a principal explanatory variable in thermal-performance analysis.

The benefit of additional airflow is therefore context-dependent. Where the dominant problem is sensible heat, increasing mass flow can reduce the temperature rise of the air for a given heat load. Where the incoming air is already warm and humid, the same increase may produce a smaller improvement in perceived thermal conditions, especially if evaporative cooling is constrained. Computational work on underground thermal

management has likewise shown that ventilation rate interacts with cooling load, virgin rock temperature and machinery heat rather than acting as an isolated control variable. This interaction is one reason why a single universal 'optimal airflow' cannot be defined without specifying the thermal load, contaminant constraints and resistance of the particular network.

2.5 Relative Humidity and the Occupational Thermal Environment

Relative humidity is not merely a comfort variable. In warm underground environments, high humidity reduces the evaporative potential of sweat and can intensify physiological heat strain. The effect is particularly important in deep mines, where high rock temperature and water sources may produce simultaneously high dry-bulb temperature and humidity. A 2025 field and experimental study in a deep hot-humid underground environment evaluated the thermal responses of miners at approximately 1,015 m depth and confirmed the importance of environmental conditions in perceived thermal stress [15].

Recent coupled heat–moisture research also treats temperature and humidity as dynamic variables rather than independent descriptors. Shi et al. developed a predictive micro-environmental framework for occupational heat stress in deep mine roadways based on coupled heat and moisture behaviour [16]. Such approaches reinforce the need to include humidity when assessing whether an airflow increase actually produces an acceptable thermal environment. A larger air quantity may improve convective heat transfer, but its benefit can be constrained when the incoming or locally humidified air already has a high moisture content.

From a thermodynamic perspective, relative humidity is best interpreted together with humidity ratio and moist-air enthalpy. Relative humidity alone is strongly temperature-dependent, whereas humidity ratio represents the actual mass of water vapour associated with the dry air. Enthalpy combines the sensible contribution of air temperature with the latent contribution of water vapour and is therefore a more informative state variable for comparing warm-humid ventilation conditions. Chu et al. [2] used airflow enthalpy in field assessment of a hot and humid underground tunnel and showed that changes along the airway can reveal the location and magnitude of heat and moisture addition. For engineering analysis, this provides a stronger physical basis than treating humidity as a purely descriptive comfort parameter.

2.6 Ventilation-on-Demand and Variable Airflow Control

Because fan power is highly sensitive to airflow and pressure, ventilation-on-demand (VoD) has become a major strategy for reducing underground ventilation energy. The basic concept is to provide the required air where and when it is needed rather than maintaining the entire network continuously at a conservative maximum condition. Kumar et al. analysed VoD in an Indian underground coal mine and reported meaningful energy-saving potential through demand-based operation [5].

Recent research extends this concept through sensors, predictive models and adaptive fan control. Ihsan et al. proposed a neuro-fuzzy VoD system and reported laboratory-scale reductions in fan power while maintaining dilution objectives [17]. A 2026 critical review of modern underground mine ventilation strategies concluded that the most consistently supported savings arise from reducing network resistance and pressure losses, adjusting fan speed, and matching airflow distribution to actual operational requirements; it also cautioned that CFD and monitoring are enabling tools rather than energy-saving measures by themselves [4].

The safety constraint remains decisive. Airflow cannot be reduced solely because an energy model predicts lower fan power. Minimum quantities and velocities must continue to satisfy contaminant dilution, fire and emergency requirements, equipment emissions and local thermal constraints. A recent simulation-driven study of battery-electric vehicles combined with VoD showed that electrification can reduce heat and emissions, but that air-velocity limits may become the controlling constraint when airflow is reduced [18]. Thus, energy-efficient control requires explicit environmental and safety boundaries.

2.7 Statistical and Simulation Approaches to Ventilation Performance

Physical equations provide the governing relationships, but mine ventilation performance is affected by multiple variables simultaneously. Statistical methods are therefore useful for separating the contribution of airflow, humidity, temperature and pressure drop and for quantifying uncertainty. Multiple regression is particularly appropriate when the objective is to estimate the partial effect of one operating variable while holding the others constant. Group comparisons can additionally determine whether low, moderate and high operating ranges produce practically distinct performance levels.

Simulation is valuable when measured data are unavailable or when controlled variation of mine conditions would be unsafe or impractical. It allows transparent sensitivity analysis and can identify which variables should be prioritized in a later measurement campaign.

However, simulation-derived inferential statistics must be interpreted carefully: a small p-value within a generated dataset does not establish population-level evidence for operating mines. Validation against field measurements remains necessary before regression coefficients can be used as design or operational rules.

Optimization research increasingly combines ventilation-network simulation with control algorithms. Earlier work on fan-speed optimization under ventilation-on-demand and time-of-use tariffs demonstrated that network constraints and fan laws can be incorporated into an energy-minimization formulation [6]. More recent research continues this direction with adaptive and cloud-enabled control architectures [19]. The present study deliberately uses a simpler statistical framework so that the influence of the physical variables remains transparent.

Fan design itself remains another important efficiency lever. A 2024 study of an axial-flow mine ventilation fan combined computational fluid dynamics, experimental validation, design-of-experiments and regression to quantify the influence of blade and operating parameters, reporting substantial deterioration under stall conditions and measurable gains from geometry optimization [20]. This illustrates why a mine-level energy model should ultimately be linked to actual fan characteristic curves rather than assuming a constant efficiency.

At the system level, recent work has also focused on integrating ventilation simulations with demand-response logic. Nikolaev and Kychkin developed a framework in which mine-ventilation process simulations support predefined control actions based on real-time sensing and main-fan regulation [21]. Such approaches are relevant because underground ventilation has high inertia: a change in fan command does not instantaneously produce the desired environmental state throughout an extended network.

Energy-efficiency research is also expanding beyond demand reduction to energy recovery. A 2025 study investigated the integration of a hybrid vertical-axis wind turbine with mine ventilation exhaust air, using aerodynamic modelling and CFD to evaluate pressure distribution, fan interaction and recovery potential [22]. Although exhaust-energy recovery is outside the scope of the present analysis, it reinforces the need to treat pressure, airflow and fan operating conditions as coupled energetic variables.

The broader decarbonisation literature similarly places ventilation within a system-level mine-energy context. Reviews of mining energy consumption emphasize that electrification, renewable integration and efficiency measures must be evaluated together because changes in equipment fleets alter underground heat and contaminant loads and therefore change ventilation demand [23]. Recent inverse-optimization research on mine ventilation fans further demonstrates the continuing shift from fixed-schedule operation toward adaptive efficiency maximization [24].

Taken together, the literature suggests that energy-efficient mine ventilation is not a single-component problem. Network resistance determines the pressure requirement, fan characteristics determine how efficiently that pressure is produced, operational demand determines the airflow that is actually necessary, and the underground heat and moisture balance determines whether the resulting environment is thermally acceptable. Modern control methods can coordinate these elements, but their outputs remain meaningful only when the underlying physical relationships are explicit. For that reason, there is still value in comparatively simple models that preserve the connection between airflow, pressure, humidity and temperature and that can be audited without relying on an opaque optimization procedure.

2.8 Research Gap and Contribution of the Present Study

The literature establishes several relationships individually: airflow affects both thermal transport and fan energy; pressure losses determine the mechanical effort required to move air; humidity modifies the underground thermal environment; and demand-responsive control can reduce unnecessary ventilation energy. Fewer studies present these variables together in a compact statistical framework that is sufficiently transparent to be reproduced and subsequently replaced with site measurements.

The present paper addresses this need through a reproducible simulation-based analysis in which airflow rate, relative humidity, inlet temperature and pressure drop are varied jointly. The contribution is methodological rather than site-specific. First, fan power is linked explicitly to airflow, pressure rise and efficiency. Second, temperature and humidity are translated into humidity ratio and moist-air enthalpy so that moisture is represented as part of the thermodynamic state rather than as an isolated percentage. Third, regression and group comparisons are used to show how the energetic and thermal responses change across the simulated operating domain. The resulting framework is intentionally simple enough to be recalculated from the accompanying dataset and to serve as a basis for subsequent calibration with measurements from an operating mine.

3. Materials and Methods

3.1 Research Design and Data Source

The study adopted a reproducible, simulation-based engineering design with 90 independent operating scenarios. No field measurements are claimed and the generated observations are not attributed to a named mine. Airflow rate was sampled between 8 and 26 m³/s, relative humidity between 45% and 90%, inlet dry-bulb temperature between 24 and 34°C, and system pressure drop between 650 and 1550 Pa. Fan efficiency was centred on 72% and restricted to 62–80%. The ranges create a controlled sensitivity domain in which the energetic consequence of airflow and the thermo-hygrometric consequence of temperature and humidity can be studied separately. A fixed random seed was used so that the dataset and all reported statistics can be reproduced.

The selected ranges were not intended to reproduce the design limits of every underground mine. Instead, they define a broad but manageable operating envelope in which the variables can change sufficiently to reveal their individual effects. This is important in a sensitivity study because a very narrow range can hide relationships that are physically present, whereas unrealistically extreme values can dominate the regression. The 90 scenarios therefore represent controlled combinations of plausible ventilation and thermo-hygrometric conditions rather than 90 observations collected from production. Random variation was retained within the defined limits to avoid constructing a perfectly regular factorial dataset and to make the statistical analysis closer to the variability expected in later field measurements.

3.2 Performance Indicators

The energetic model was based on the standard air-power balance, while the thermo-hygrometric state of the ventilation air was additionally characterized using humidity ratio and moist-air enthalpy. This separation is important because relative humidity does not directly determine fan shaft power, whereas it materially changes latent heat content and thermal exposure. The formulation follows the heat-transfer and energy-balance framework used in engineering analysis [7, 8, 9, 10, 11] and is consistent with mine studies that evaluate airflow thermodynamic parameters and enthalpy in hot-humid underground workings [2, 16].

Table 1. Study variables and definitions

Variable	Type	Unit	Role
Airflow rate	Independent	m ³ /s	Ventilation air quantity
Relative humidity	Independent	%	Moisture condition
Inlet temperature	Independent	°C	Thermal boundary condition
Pressure drop	Independent	Pa	Network load
Fan electrical power	Dependent	kW	Electrical demand
Thermal effectiveness	Dependent	%	Simulated thermal index
Specific ventilation energy	Dependent	kW/(m ³ /s)	Power per unit airflow
Heat-stress proxy	Dependent	-	Comparative, non-regulatory index

Fan Power and Specific Ventilation Energy

For each scenario, fan electrical power was calculated from the air-power relation $P_{\text{fan}} = Q \cdot \Delta p / \eta$, where P_{fan} is electrical fan power (kW), Q is volumetric airflow rate (m³/s), Δp is the pressure rise required to overcome network resistance, and η is total fan efficiency. Specific ventilation energy was defined as $\text{SVE} = P_{\text{fan}} / Q$. At constant efficiency, greater airflow or pressure requirement increases fan power. For a fixed-resistance network, Δp is approximately proportional to Q^2 ; consequently, fan power can approach a cubic dependence on airflow. This affinity-law behaviour is used as a physical interpretive benchmark rather than imposed on the independently sampled pressure-drop scenarios.

Psychrometric Characterization of the Ventilation Air

To provide a physically interpretable moisture basis, humidity ratio was calculated at an assumed barometric pressure of 101.325 kPa. Saturation vapor pressure p_{ws} was estimated from dry-bulb temperature, vapor partial pressure was obtained as $p_{\text{v}} = \phi \cdot p_{\text{ws}}$, and humidity ratio as $w = 0.62198 \cdot p_{\text{v}} / (P - p_{\text{v}})$, where ϕ is relative humidity expressed as a fraction. Moist-air specific enthalpy was then calculated as $h = 1.006T + w(2501 + 1.86T)$, in kJ/kg dry air. Enthalpy combines sensible and latent contributions; field research in hot and humid underground workings has likewise used airflow enthalpy to characterize accumulated heat and moisture loads [2]. Recent deep-mine research further supports coupled heat–moisture assessment rather than temperature alone [16].

Thermal Performance Response and Heat-Stress Proxy

The reported thermal-effectiveness variable is a bounded simulation response used for comparative sensitivity analysis, not a measured efficiency of a specific mine installation. It was constructed to increase with airflow and decrease with relative humidity, inlet temperature and pressure burden, with a small stochastic residual added to avoid a perfectly deterministic dataset. Likewise, the heat-stress variable is a comparative proxy that increases with inlet temperature and relative humidity and decreases with airflow. It must not be interpreted as WBGT, PHS, UTCI or any statutory occupational exposure index. This distinction is retained because field evidence shows that actual underground thermal exposure depends on coupled temperature, humidity, airflow, rock heat, machinery heat and local recirculation [12, 15, 16].

The thermal-effectiveness response is used here as a normalized comparative indicator rather than as a standardized equipment efficiency. Its purpose is to express, on a common scale, the expected direction of improvement when airflow increases and the expected deterioration when temperature, humidity and pressure burden increase. The same logic applies to the comparative thermal-stress response. These two variables allow the statistical workflow to be demonstrated, but they are deliberately kept separate from the psychrometric quantities, which are calculated from established thermodynamic relations. In a field study, both synthetic responses should be replaced by directly measurable outcomes such as outlet temperature, sensible/latent heat removal and a recognized occupational heat-stress index.

Modelling Assumptions and Reproducibility

The model assumes steady operating points, constant atmospheric pressure for psychrometric calculations, no explicit air leakage, and no spatially resolved heat exchange with rock surfaces. Pressure drop is treated as an input variable rather than solved from a complete mine resistance network. Consequently, the simulation is a controlled engineering sensitivity study, not a calibrated digital twin. The complete scenario dataset is retained as a reproducibility supplement so that the descriptive statistics, correlations and regression models can be recalculated.

3.3 Statistical Analysis

Descriptive statistics (minimum, maximum, mean and standard deviation) were calculated for all continuous variables. Pearson correlation coefficients described bivariate linear associations. Multiple ordinary least-squares regression models used airflow rate, relative humidity, inlet temperature and pressure drop as simultaneous predictors of fan power, thermal effectiveness, specific ventilation energy and the comparative heat-stress proxy. Airflow was classified as low (≤ 14 m³/s), moderate (>14 to 20 m³/s) and high (>20 m³/s), followed by one-way ANOVA for between-group comparisons. Statistical significance was assessed at $p < 0.05$. Because the observations are generated by a specified simulation design, inferential p-values quantify separation inside this synthetic design space and are not evidence of population effects in operating mines. Interpretation therefore emphasizes effect direction, magnitude and R^2 rather than significance alone.

Before interpreting the regression coefficients, the simulated design was checked conceptually against the governing equations. Fan power was expected to respond most strongly to airflow and pressure drop, while the psychrometric state was expected to respond to inlet temperature and relative humidity. The statistical models were therefore used to quantify relationships already motivated by engineering theory, not to search blindly for associations. This distinction is particularly important for a generated dataset: agreement between model output and physical expectation is a consistency check, whereas disagreement would indicate that the simulation assumptions require revision.

4. Results

4.1 Descriptive Statistics

The 90 scenarios covered an airflow range of 8.13–25.56 m³/s and a relative-humidity range of 46.0–89.7%. Mean fan power was 25.91 kW (SD = 9.15), and mean thermal effectiveness was 88.96% (SD = 6.15).

Table 2. Descriptive statistics for simulated variables (N = 90)

Variable	Minimum	Maximum	Mean	SD
Airflow rate (m ³ /s)	8.13	25.56	16.91	4.92
Relative humidity (%)	45.97	89.66	67.13	13.03
Inlet temperature (°C)	24.14	33.72	28.79	3.01
Pressure drop (Pa)	689.13	1531.61	1109.41	250.74
Fan power (kW)	6.08	52.23	25.91	9.15
Thermal effectiveness (%)	77.32	98.00	88.96	6.15
Specific energy	0.71	2.15	1.54	0.34
Heat-stress proxy	17.68	28.67	23.06	2.72

Thermo-hygrometric State of the Simulated Air

At the assumed atmospheric pressure, the modelled humidity ratio ranged from 0.0091 to 0.0293 kg water/kg dry air. Moist-air enthalpy ranged from 48.5 to 108.9 kJ/kg dry air, with a mean of 72.4 kJ/kg dry air (SD 14.1). These derived quantities are not additional independent inputs; they translate the imposed temperature and relative-humidity conditions into thermodynamic state variables and make the latent contribution of moisture explicit.

The descriptive ranges confirm that the scenarios cover markedly different ventilation duties. The lower end represents comparatively modest airflow and moisture loading, whereas the upper end combines higher air quantities with warm and potentially humid inlet states. The enthalpy interval is especially informative: its width shows that the latent contribution of water vapour changes appreciably across the simulation even when the dry-bulb temperature range is only 10°C. This supports the decision to retain humidity as an explicit explanatory variable rather than describing the thermal environment only through temperature.

4.2 Correlation Analysis

Airflow was positively correlated with fan power ($r = 0.742$) and thermal effectiveness ($r = 0.386$), and negatively correlated with the heat-stress proxy ($r = -0.235$). Relative humidity was negatively associated with thermal effectiveness ($r = -0.794$) and positively associated with the heat-stress proxy ($r = 0.441$).

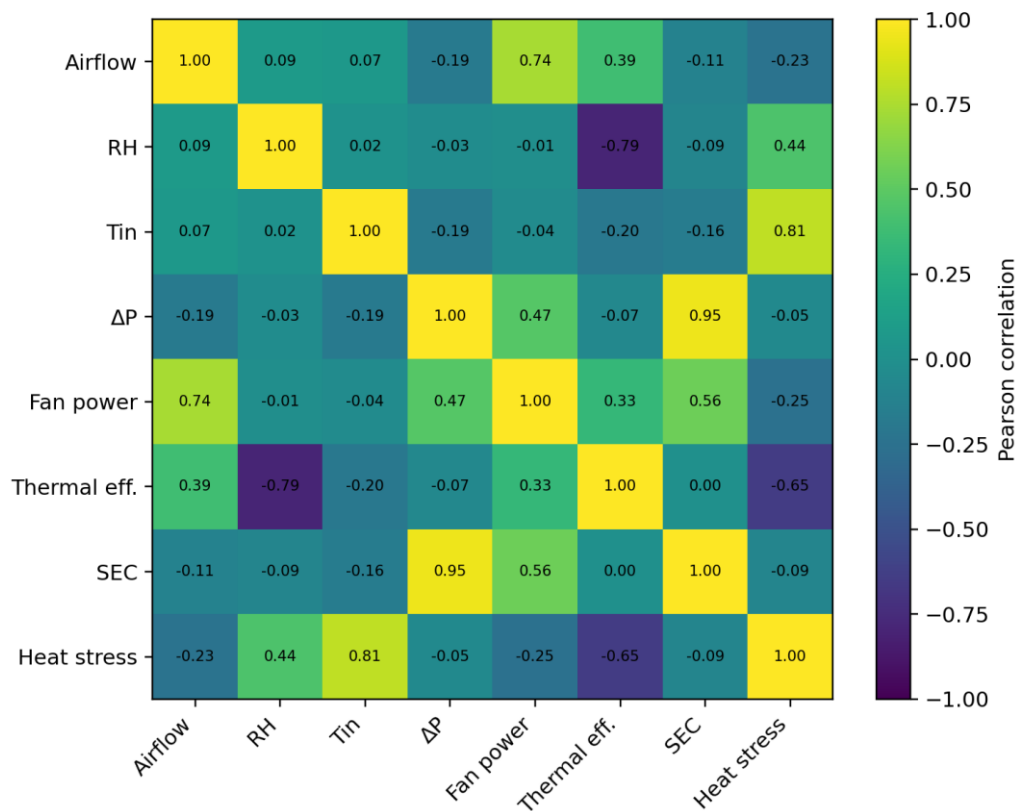


Fig. 1. Pearson correlation matrix for the simulated ventilation variables.

The correlation pattern also illustrates why a multivariable analysis is required. Airflow has the expected positive association with fan power, but fan power is not determined by airflow alone because pressure drop and efficiency also enter the power balance. Similarly, the negative association between relative humidity and thermal effectiveness does not imply that humidity acts independently of temperature. In a warm ventilation stream, the two variables jointly determine the moisture content and enthalpy of the air. The correlation coefficients are therefore best read as an initial description of the simulated relationships, while the regression models provide the more useful partial-effect interpretation.

4.3 Multiple Regression Analysis

The fan-power regression explained 93.6% of the simulated variance ($R^2 = 0.936$). Holding the other predictors constant, airflow had a coefficient of 1.605 kW per m³/s and pressure drop had a coefficient of 0.0230 kW/Pa.

The thermal-effectiveness model explained 88.7% of the variance. The airflow coefficient was 0.584 percentage points per m³/s, whereas relative humidity had a coefficient of -0.392 percentage points per 1% RH.

Table 3. Multiple linear regression summary

Dependent variable	R ²	Airflow B	RH B	Tin B	ΔP B	Model p
Fan power	0.936	1.605	-0.049	0.069	0.02302	<.001
Thermal effectiveness	0.887	0.584	-0.392	-0.446	-0.00107	<.001
Specific energy	0.910	0.005	-0.002	0.002	0.00131	<.001
Heat-stress proxy	0.950	-0.178	0.094	0.754	0.00061	<.001

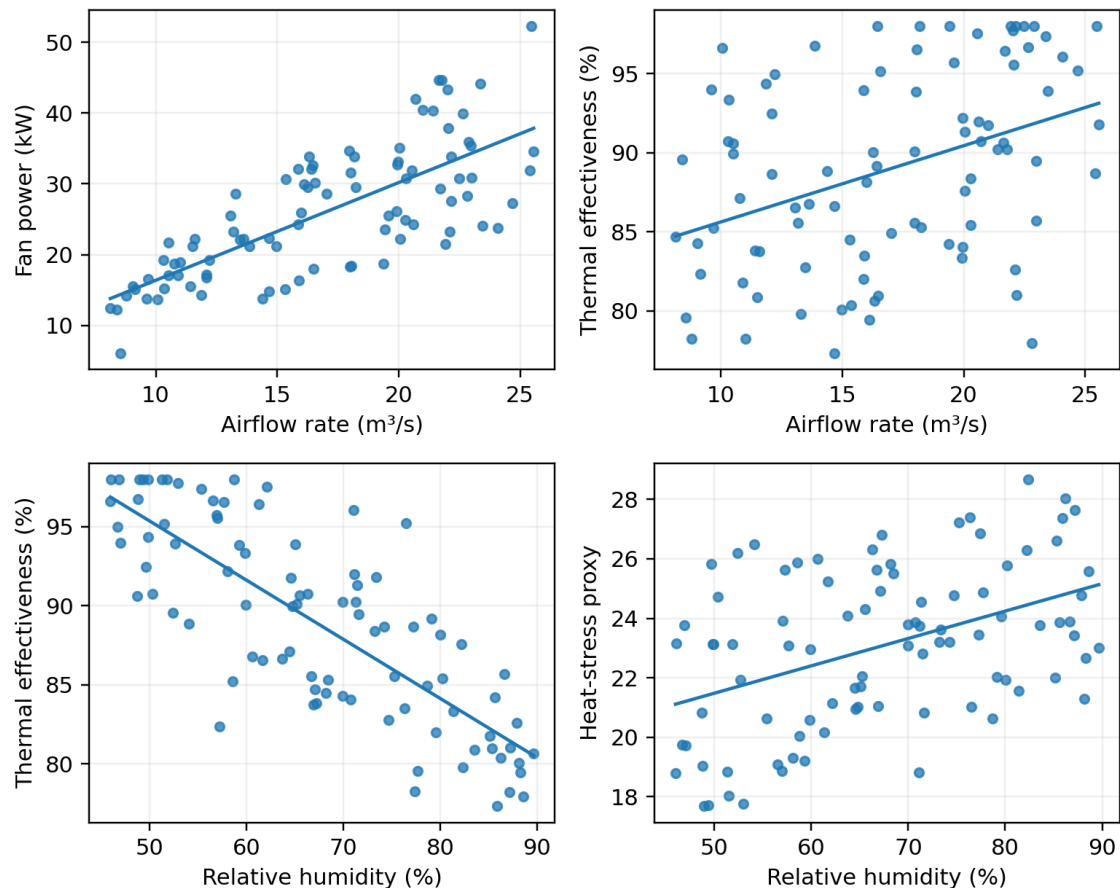


Fig. 2. Selected bivariate relationships illustrating the simulated energy–thermal trade-off

The high R² obtained for fan power is consistent with the relatively direct physical relation used to generate this response. The thermal-effectiveness model is less purely mechanical because its response combines several environmental variables and a residual term. This difference is useful rather than problematic: it shows why energy consumption can often be predicted from a compact set of engineering variables, whereas thermal conditions in underground workings are more sensitive to local heat and moisture sources. The coefficients should nevertheless be interpreted only within the simulated ranges; extrapolating them beyond the stated airflow, temperature, humidity or pressure intervals would not be justified.

4.4 Comparison across Airflow Groups

The ANOVA for fan power was statistically significant, $F(2, 87) = 41.75$, $p < .001$.

The ANOVA for thermal effectiveness was statistically significant, $F(2, 87) = 6.64$, $p = 0.002$.

The ANOVA for specific ventilation energy was not statistically significant, $F(2, 87) = 0.79$, $p = 0.457$.

The ANOVA for heat-stress proxy was not statistically significant, $F(2, 87) = 1.20$, $p = 0.305$.

The group comparison adds an operational view to the continuous regression results. A statistically significant increase in fan power across airflow categories is expected because the groups represent progressively larger quantities of air being moved through the system.

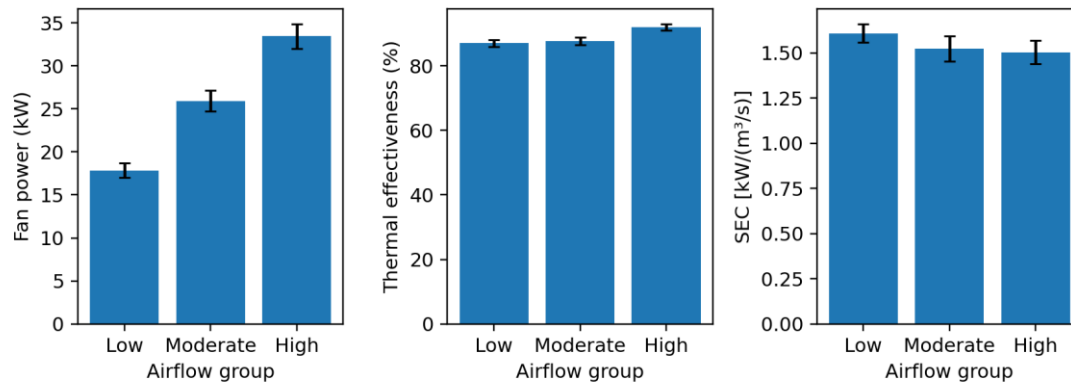


Fig. 3. Mean performance across low, moderate and high airflow groups. Error bars represent standard errors

The absence of a significant group effect for specific ventilation energy is also informative: increasing airflow does not automatically imply that each unit of delivered airflow becomes less efficient when pressure and fan efficiency vary independently. In practice, this indicator would be particularly useful for comparing shifts, branches or fan configurations that deliver similar quantities under different resistance conditions. The non-significant group result for the comparative thermal-stress response further cautions against using airflow category alone as a surrogate for the underground thermal environment; humidity and inlet temperature remain important within each group.

5. Discussion

5.1 Interpretation of the Airflow–Energy Relationship

The results reproduce the expected engineering relationship: delivering more air requires more fan power when pressure resistance is maintained. Pressure drop is also a major energetic driver, confirming that airflow targets cannot be evaluated independently of network resistance. De Souza [3] showed that mine ventilation can represent a major share of mine energy demand and that avoidable resistance within fan assemblages can consume a substantial part of fan input. This supports interpreting the present regression not merely as a statistical association, but as a reflection of the air-power balance $P = Q\Delta p/\eta$. The result is also consistent with the broader thermodynamic principle that real mechanical systems must be evaluated through both useful fluid work and installation losses [9, 10, 11].

Specific ventilation energy complements absolute fan power by normalizing electrical demand to the amount of air delivered. In practical terms, this distinction matters because a high-power fan is not necessarily inefficient if it is supplying a correspondingly large and necessary airflow against a justified pressure rise. Conversely, a smaller fan may still operate inefficiently if much of its pressure is dissipated across avoidable restrictions. Tracking both absolute power and a normalized indicator can therefore help separate changes caused by production demand from changes caused by deterioration of the ventilation network or operation away from the efficient region of the fan curve.

An important consequence is that airflow reduction and resistance reduction are not equivalent interventions. Reducing airflow lowers the quantity of air delivered and may affect safety or thermal conditions, whereas reducing avoidable resistance can lower pressure demand without intentionally reducing the required air quantity. Fan-speed optimization studies have therefore formulated energy minimization subject to ventilation-network and fan-law constraints [6]. Chatterjee et al. [6], for example, demonstrated that ventilation-on-demand and time-of-use scheduling can produce large energy savings when fan speed is matched to network requirements rather than held at a fixed maximum condition.

Fan hardware and operating point also matter. Fakhari and Mrad [20] reported a pronounced efficiency deterioration under stall conditions and showed that design and operating parameters can materially change axial-fan performance. The constant-efficiency range used in the present simulation is therefore a deliberate simplification. In a field-calibrated extension, measured fan curves and variable-speed-drive efficiency should replace the bounded synthetic efficiency variable.

This interpretation is also relevant when evaluating retrofits. Replacing a fan or installing a variable-speed drive can improve performance, but the expected saving may not be achieved if the network continues to impose excessive resistance. Conversely, relatively modest civil or maintenance interventions—such as correcting restrictive transitions, reducing leakage or revising regulator settings—can lower the required pressure while leaving the useful airflow unchanged. De Souza [3] emphasizes precisely this system-level view

of fan assemblages. For mine operators, the practical message is that fan efficiency and network efficiency should be audited together rather than treated as separate maintenance topics.

5.2 Influence of Airflow and Humidity on Thermal Performance

Within the simulated range, increased airflow improved thermal effectiveness and reduced the comparative heat-stress response. The direction agrees with heat-transfer theory [7] and with underground studies identifying airflow as an important variable in heat management [12, 13, 14]. Nie et al. [12] reported improved underground environmental conditions after ventilation-network optimization and cooling intervention, while Chu et al. [2] showed that airflow thermodynamic parameters and enthalpy can be used to track heat and moisture accumulation along hot-humid underground workings. These studies support treating airflow, temperature and moisture as coupled variables rather than independent descriptors.

Relative humidity acted in the opposite direction to airflow in the simulated thermal response. This behaviour is physically plausible because higher humidity increases the latent component of moist-air enthalpy and reduces evaporative cooling potential. Field and experimental work at approximately 1,015 m depth reported hot-humid conditions with relative humidity around 79–89% and demonstrated substantial physiological and perceptual thermal strain [15]. The present enthalpy calculation therefore strengthens the interpretation of humidity as a thermodynamic state variable, while avoiding the stronger claim that relative humidity alone determines occupational heat stress.

The heat-stress proxy used here is intentionally non-regulatory. Field application should replace it with a recognized occupational index and measured psychrometric variables.

The psychrometric results add another layer to this interpretation. Across the simulated states, moist-air enthalpy varied much more widely than dry-bulb temperature alone might suggest. This means that two shifts with similar air temperatures could still impose different thermal burdens if their moisture contents differ. In a field campaign, simultaneous measurement of dry-bulb temperature, relative humidity and airflow would therefore provide substantially more information than temperature logging alone. Where wet-bulb or globe-temperature measurements are available, the analysis could be extended to a recognized heat-stress index and the present comparative response could be removed entirely.

5.3 Operational Implications

The practical implication is not that airflow should be maximized. Higher airflow improved the simulated thermal response but increased fan electrical demand. The engineering objective is to identify the lowest airflow that satisfies contaminant, thermal and statutory constraints while minimizing avoidable pressure losses. This is the operating logic underlying VoD strategies [5, 6, 17]. Kumar et al. [5] demonstrated energy-saving potential for VoD in an Indian underground coal mine, while later control research has extended demand matching through predictive and adaptive approaches [17, 19, 21].

The results also support a hierarchy of interventions: first reduce unnecessary network resistance and leakage, then operate fans efficiently, and only then vary airflow according to validated demand. This avoids using airflow reduction as a substitute for poor network design [3, 4].

Recent work also illustrates why energy optimization must remain subordinate to safety constraints. In a 2026 simulation study at Turquoise Ridge Mine, the integration of battery-electric vehicles and VoD reduced ventilation-related energy and emissions, but minimum air velocity became the controlling constraint as airflow was reduced [18]. This is directly relevant to the present study: a low-power operating point is not automatically an acceptable ventilation operating point.

At a broader system level, ventilation efficiency interacts with mine electrification and decarbonisation. Roemer et al. [23] identify ventilation among the major energy consumers of underground mines and emphasize integrated energy management. Emerging approaches range from exhaust-air energy recovery [22] to inverse optimization of fan efficiency [24]. These developments indicate that the simple energy–thermal trade-off analysed here can serve as a transparent baseline for more advanced control, provided that future models retain explicit physical and safety constraints.

For implementation, this suggests a staged decision process rather than a single optimization target. The first stage is to establish the minimum ventilation duty from gas, dust, diesel or battery-electric equipment, blasting, occupancy and thermal requirements. The second is to examine whether the network can deliver that duty with lower pressure losses. Only after these constraints are understood should fan speed or airflow distribution be varied dynamically. Such a sequence is less mathematically elegant than optimizing energy alone, but it reflects how ventilation decisions are made in a safety-critical industrial system: the feasible operating region is defined first, and energy minimization takes place inside that region.

The same framework can support future data collection. A practical monitoring dataset would ideally synchronize fan electrical power, fan speed, branch airflow, static pressure, dry-bulb temperature and relative humidity with production state and equipment location. Repeated measurements over different shifts and seasons would then allow the present regression structure to be tested against real variability. If the measured pressure–flow relation is sufficiently stable, network resistance coefficients could be estimated and the simple $P = Q\Delta p/\eta$ relation could be linked directly to fan curves. At that stage, the model would move from a sensitivity exercise toward a mine-specific operational tool.

6. Limitations

The main limitation of the study is also the reason for its transparency: the dataset is synthetic and has not been calibrated against measurements from a particular underground mine. Pressure drop was varied as an independent input rather than calculated from a complete resistance network, and the model does not resolve leakage, airway roughness, branch interactions, fan curves, variable-speed-drive losses or changes in air density with depth. The thermal side is similarly simplified. Rock temperature, machinery heat, groundwater, evaporation and transient heat storage are not solved explicitly, although each can be important in deep workings. The results should therefore be interpreted as a controlled sensitivity analysis of physically motivated variables, not as predicted performance for a named mine.

A second limitation concerns the two normalized thermal responses. Thermal effectiveness and the comparative thermal-stress response are generated indicators designed to demonstrate the statistical workflow; they are not standardized mine-performance metrics. In particular, the thermal-stress response must not be interpreted as WBGT, PHS, UTCI or a regulatory exposure limit. The psychrometric quantities included in the revised analysis—humidity ratio and moist-air enthalpy—have a direct thermodynamic definition and are therefore stronger physical outputs. A field version of the study should replace the synthetic responses with measured inlet/outlet states, heat-removal rates and a recognized occupational heat-stress metric.

A third limitation is the steady-state treatment of each scenario. Real ventilation networks have inertia, production cycles and delayed environmental responses. A fan-speed change may alter airflow rapidly near the fan while temperature, humidity and contaminant concentrations respond differently in distant workings. Likewise, the efficiency of a real fan varies with its operating point and cannot be represented completely by a bounded efficiency range. Future work should therefore combine time-resolved measurements with a network solver and actual fan characteristic curves, then test whether the relationships observed in this simulation remain stable across shifts, seasons and production states.

7. Conclusions

This study examined the combined energetic and thermal implications of airflow rate, relative humidity, inlet temperature and pressure drop in underground mine ventilation using 90 reproducible simulation scenarios. The analysis was intentionally structured around transparent engineering relationships. Fan power was linked to airflow, pressure rise and efficiency, while the moisture state of the ventilation air was described through humidity ratio and moist-air enthalpy. Statistical analysis was then used to quantify how these variables interact across the selected operating envelope rather than to replace the underlying thermodynamic interpretation.

The results show a clear energy–thermal trade-off. Increasing airflow improved the simulated thermal response, but it also increased electrical fan demand. Pressure drop emerged as a central energetic variable, reinforcing the importance of reducing avoidable network resistance before treating airflow reduction as an energy-saving measure. Relative humidity had an adverse influence on the simulated thermal response and substantially changed moist-air enthalpy, confirming that underground thermal assessment should consider moisture together with temperature. These findings are consistent with the broader literature on mine ventilation, heat management and ventilation-on-demand [2, 3, 6, 15].

From an operational perspective, the preferred objective is therefore not maximum airflow and not minimum airflow, but sufficient airflow delivered with the lowest reasonable pressure and fan losses while all safety and thermal constraints remain satisfied. The framework presented here can be used as a reproducible baseline for that reasoning. Its next development should be field validation with synchronized measurements of airflow, pressure, temperature, humidity, fan speed and electrical power, together with a recognized heat-stress metric. Once calibrated, the same structure could support mine-specific sensitivity analysis, comparison of operating strategies and, subsequently, constrained optimization of ventilation energy.

Acknowledgements

The authors acknowledge the scientific and technical literature that supported the development of the thermodynamic and ventilation framework used in this study. The assumptions, simulation design, calculations and interpretation of the results remain the responsibility of the authors.

References

- [1] **McPherson M.J.**, 1993
Subsurface Ventilation and Environmental Engineering, Chapman & Hall, London.
- [2] **Chu Z., Zhou G., Rao Z., Wang Y., Zhao X.**, 2022
Field measurement and assessment on airflow thermodynamic parameters in hot and humid underground tunnelling: A case study, Tunnelling and Underground Space Technology, 121, 104341. <https://doi.org/10.1016/j.tust.2021.104341>
- [3] **De Souza E.**, 2015
Improving the energy efficiency of mine fan assemblages, Applied Thermal Engineering, 90, 1092–1097.
<https://doi.org/10.1016/j.applthermaleng.2015.04.048>
- [4] **Bajic S., Gaćina R., Crnogorac L., Urošević K.**, 2026
Energy efficiency of modern underground mine ventilation control strategies: A critical review of research findings, Podzemni radovi. <https://doi.org/10.5937/podrad2648133B>
- [5] **Kumar M., Maity T., Kirar M.K.**, 2022
Energy savings through VOD (ventilation-on-demand) analysis in Indian underground coal mine, IEEE Access, 10, 93525–93533. <https://doi.org/10.1109/ACCESS.2022.3203710>
- [6] **Chatterjee A., Zhang L., Xia X.**, 2015
Optimization of mine ventilation fan speeds according to ventilation on demand and time of use tariff, Applied Energy, 146, 65–73. <https://doi.org/10.1016/j.apenergy.2015.01.134>
- [7] **Petrilean D.C.**, 2016
Transmiterea căldurii, Editura Universitas, Petroșani.
- [8] **Petrilean D.C.**, 2008
Elaborating and Analysing the Real Balance of Heat for the Steam Generator RGL 10/DD, Annals of the University of Petroșani, Mechanical Engineering, 10, 155–160. ISSN 1454-9166.
- [9] **Petrilean D.C.**, 2006
Compresoare elicoidale, Editura Tehnica-Info, Chișinău, ISBN 978-9975-63-289-8.
- [10] **Petrilean D.C.**, 2009
Method of Calculus for the Power Input of the Helical Screw Compressor, U.P.B. Scientific Bulletin, Series D: Mechanical Engineering, 71(4), 121–130. ISSN 1454-2358.
- [11] **Petrilean D.C.**, 2009
The Study of Energy Losses through Case Helical Screw Compressor, Bulletin of the Transilvania University of Brașov, Proceedings of the Internationally Attended National Conference on Thermodynamics, Vol. 2(51), Series I, 235–241. ISSN 2065-2119, ISBN 978-973-598-521-9.
- [12] **Nie X., Wei X., Li X., Lu C.**, 2018
Heat treatment and ventilation optimization in a deep mine, Advances in Civil Engineering, 2018, 1529490.
<https://doi.org/10.1155/2018/1529490>
- [13] **Dosa I., Anuțoiu S., Petrilean D.C., Urdea G.**, 2022
Influence of ambient temperature on the efficiency of underground spot cooling system, MATEC Web of Conferences, 354, 00026. <https://doi.org/10.1051/matecconf/202235400026>
- [14] **Ihsan A., Cheng J., Widodo N.P., Wang E. et al.**, 2024
Hybrid method for analyzing air thermal conditions in underground mines, Expert Systems with Applications, 245, 123026. <https://doi.org/10.1016/j.eswa.2023.123026>
- [15] **Wang X., Wang Y., Lai X., Wang G., Sang C.**, 2025
Investigation of heat stress and thermal response in deep hot-humid underground environments: A field and experimental study, Building and Environment, 270, 112506. <https://doi.org/10.1016/j.buildenv.2024.112506>

[16] **Shi P. – et al.**, 2026

Dynamic assessment of occupational heat stress in deep mine roadways: A coupled heat-moisture model for predictive microenvironmental analysis, Environmental Research, 294, 123864. <https://doi.org/10.1016/j.envres.2026.123864>

[17] **Ihsan A., Widodo N.P., Cheng J., Wang E. et al.**, 2024

Ventilation on demand in underground mines using neuro-fuzzy models: Modeling and laboratory-scale experimental validation, Engineering Applications of Artificial Intelligence, 133, 108048. <https://doi.org/10.1016/j.engappai.2024.108048>

[18] **Kahraman M., Düzgün H.Ş.**, 2026

Safety implications of integrating battery-electric vehicles with ventilation-on-demand in underground mining: A simulation-driven study at Turquoise Ridge Mine, Journal of Industrial Safety, article in press. <https://doi.org/10.1016/j.jinse.2026.06.001>

[19] **Bhukya P., Naick B.K.**, 2025

An advanced approach for cloud enabled energy efficient ventilation control of multiple main fans in underground coal mines, Computers & Electrical Engineering, 124, 110330. <https://doi.org/10.1016/j.compeleceng.2025.110330>

[20] **Fakhari S.M., Mrad H.**, 2024

Optimization of an axial-flow mine ventilation fan based on effects of design parameters, Results in Engineering, 21, 101662. <https://doi.org/10.1016/j.rineng.2023.101662>

[21] **Nikolaev A.V., Kychkin A.V.**, 2025

Development and integration of an underground mining enterprise ventilation process simulations into the demand response, Journal of Mining Institute, 275, 18–29.

[22] **Banerjee S., Maity T.**, 2025

Energy recovery from mine ventilation exhaust air using hybrid Savonius–Darrieus vertical axis wind turbine, International Journal of Ventilation, 24(4), 586–612. <https://doi.org/10.1080/14733315.2025.2521568>

[23] **Roemer, J., Mungyeke Bisulandu B.**, 2026

-J.R., Rousse, D.R., Pellerin, M., Bozorg, M., Ilinca, A. –, Energy Consumption, Decarbonization Pathways, and Renewable Energy Integration in the Mining Industry: A System-Level Review. Energies, 19(8), 1890. <https://doi.org/10.3390/en19081890>

[24] **Liu Y., Yuan K., Lu G., Li X.**, 2026

Towards intelligent mine ventilation: An inverse optimization approach for fan efficiency maximization via surrogate modeling and adaptive particle swarm optimization, Energy, 354, 141085. <https://doi.org/10.1016/j.energy.2026.141085>



This article is an open access article distributed under the Creative Commons BY SA 4.0 license. Authors retain all copyrights and agree to the terms of the above-mentioned CC BY SA 4.0 license.