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Ventilation system design and main fan selection for block 3 of the Parvadeh 4 coal mine based on three-dimensional airflow simulation

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ABSTRACT

Underground coal mine development is commonly accompanied by increasing ventilation resistance and changing airflow requirements, making the selection of a suitable main ventilation fan progressively more challenging throughout the mine life. This study presents the design of the ventilation system and the selection of the main ventilation fan for Block 3 of the Parvadeh 4 coal mine using a combination of ventilation network analysis and three-dimensional airflow simulation in VentSim. Airflow requirements for development headings and mechanized longwall panels were determined in accordance with the Iranian Coal Mine Safety Regulations, considering methane dilution, dust control, blasting gases, and workforce requirements. The VentSim model was verified by independent pressure-loss calculations based on the Atkinson equation. Three representative development stages covering a 15-year mine life were analyzed to evaluate airflow distribution, ventilation resistance, and fan operating conditions. The results showed that the total ventilation pressure loss increased from 795 Pa in Stage I to 1032 Pa in Stage II and then to 1868 Pa in Stage III as the ventilation network grew. With a design airflow of about 107 m^3/s, allowing for a 20% design allowance, the ventilation requirements for the whole life of the mine were met. The fan performance was evaluated and it was found that the single motor was sufficient for the first two development phases and the dual motor operation was required for the last development phase due to the increase in network resistance. Among the evaluated alternatives, the FBCDZ No. 24 twin-motor axial fan provided the most suitable operating range and maintained high efficiency under all planned operating conditions. The proposed procedure provides a practical approach for ventilation planning and main fan selection in mechanized underground coal mines.

KEYWORDS

Mine ventilation, ventilation network design, three-dimensional airflow simulation, main fan selection, underground coal mining

I. INTRODUCTION

Ventilation is an essential system in mechanized underground coal mining that has direct impact on safety, productivity and operational stability. Its main function is to provide fresh air for working places and to remove dangerous gases such as methane and carbon monoxide. The ventilation also reduces the concentration of coal dust, thereby reducing the risk of explosions and occupational respiratory disease. It also controls temperature and humidity, improving working conditions for miners and ensuring the reliable operation of diesel-powered equipment. Therefore, proper ventilation design is critical for safe and efficient coal production (McPherson, 1993; MSHA, 2024; NIOSH, 2019).

The deeper the coal mines, the more difficult the ventilation systems. Airway resistance, travel distance, heat production and gas emissions are all affected greatly by the increase of airflow stability. Complex mine layouts with multiple longwall panels make it difficult to maintain the necessary airflow rates whilst complying with safety standards for methane and other pollutants. Therefore, the ventilation design should rely on empirical experience as well as quantitative analysis, which involves airflow network modeling and pressure loss calculations (Tukkaraja, 2019; Noack, 1998; Kurnia et al., 2014; Cui et al., 2014; Makhmutova et al., 2022).

To overcome these challenges, three-dimensional ventilation simulation tools like VentSim are often used. They allow engineers to build up complete mine ventilation models, simulate air flow distributions and

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calculate pressure losses, and evaluate fan performance under different operating conditions (Zhang and Suo, 2016; Ventsim, 2025). The models integrate geological, geometric and operational information to permit scenario analysis throughout the life of the mine and to assist engineers in determining the proper fan capacities, regulator configurations and control strategies. This feature is particularly important in methane-rich coal seams where proper ventilation is critical for safe mining (Uripto, 2014; Chaoqun, 2013).

Sophisticated methodologies have been proposed in recent studies to improve the efficiency of ventilation and reduce energy consumption while ensuring safety. These methodologies include artificial intelligence, ventilation-on-demand (VoD), and data-driven fault diagnosis (Roy et al., 2025; Brake, 2023; Zhang and Li, 2023). However, most of the mechanized coal mines are still using traditional design methods. The combination of ventilation network analysis, three-dimensional simulation, and main fan selection for the whole life cycle of the mine is seriously restricted (Kursunoglu and Onder, 2015; Dzwiti, 2017). In the selection of main fans, it is necessary to consider the change of ventilation resistance and air volume requirements with the increase of mining depth, which has a great influence on energy consumption and mine safety (Zuoquan et al., 2022; Wan et al., 2025). Recent studies have also focused on ventilation network optimization, energy-efficient ventilation strategies, intelligent ventilation systems, and ventilation-on-demand (VoD) technologies (Karagianni and Benardos, 2021; Maleki et al., 2018; Ihsan et al., 2024; Saleem, 2025; Zhong et al., 2025).

Table 1 summarizes previous work on mine ventilation design and fan selection. Most of the current research is focusing on discrete elements like airflow simulation, CFD modeling, network analysis or fan performance evaluation. A limited number of studies simultaneously examine both ventilation system design and fan selection, with even fewer addressing long-term mine development within a cohesive framework. This reveals a distinct research gap in integrated ventilation design methodologies for mechanized coal mines.

II. CASE STUDY

Parvadeh Block 3 coal mine is located within the Parvadeh 4 coalfield in the Tabas Coal Basin, Iran, and is part of the Tabas Coal Mines Development Program implemented by IMIDRO. The mine extends over an area of approximately 9.8 km^2 and is planned to be developed using a mechanized retreat longwall mining system. The mineable coal reserves are hosted in two principal seams, namely C1 and B2. The main geological, production, and ventilation-related characteristics of the mine, together with the estimated coal reserves, are presented in Table 2. These parameters provide the input dataset for ventilation network modeling and define the boundary conditions for airflow simulation and main fan selection in this study.

Table 1. Comparison of previous studies on mine ventilation system design and fan selection

Study	3D Ventilation Simulation (VentSim)	CFD Analysis	Ventilation Network Analysis	Main Fan Selection	Long-term Mine Development	Integrated Framework
Suvar et al. (2012)	✓	–	✓	–	–	–
Kurnia et al. (2014)	–	✓	✓	–	–	–
Kursunoglu and Onder (2015)	–	–	✓	✓	–	–
Zhang and Suo (2016)	✓	–	✓	–	–	–
Dzwiti (2017)	✓	–	✓	✓	–	–
Maleki et al. (2018)	✓	–	✓	–	–	✓
Artica et al. (2019)	–	✓	✓	–	–	–
Karagianni and Benardos (2021)	–	–	✓	–	–	✓
Brake (2023)	–	–	✓	–	–	–
Zhang and Li (2023)	–	–	✓	–	–	✓
Ihsan et al. (2024)	–	–	✓	–	–	✓
Roy et al. (2025)	–	–	✓	–	–	✓
Saleem (2025)	–	–	✓	–	–	✓
Zhong et al. (2025)	–	–	✓	–	✓	✓
This study	✓	–	✓	✓	✓	✓

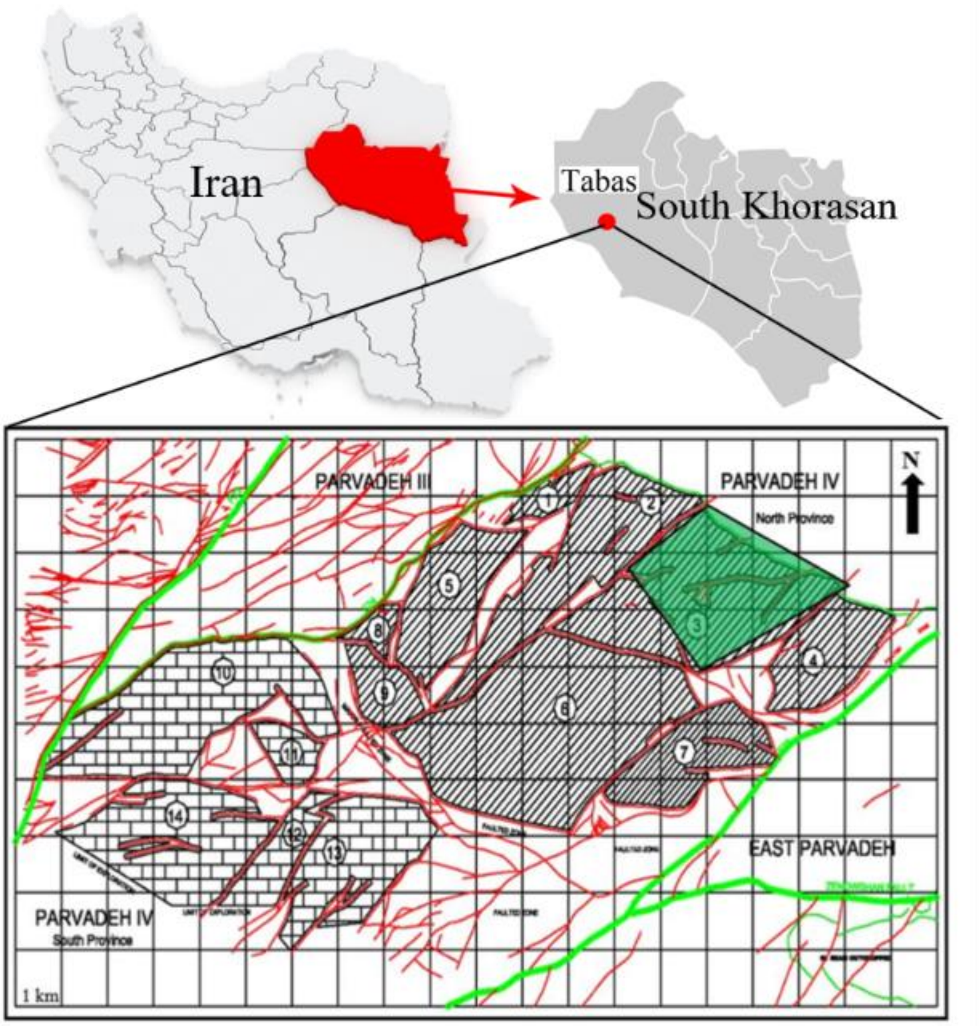


Fig. 1. A Mine map of Block 3 of the Parvadeh 4 area (After CMC, 2018)

Table 2. General characteristics of Block 3 of the Parvadeh 4 coal mine (After CMC, 2018).

Parameter	Value
Mining method	Mechanized retreat longwall
Coal seams	C1 and B2
C1 reserve	9,688,000 t
B2 reserve	10,340,000 t
Total reserve	20,028,333 t
Daily production	1,600–2,500 t/day
Number of active panels	4–6
Panel length	600 m
Panel width	150 m
Methane content	4–15 m^3/t of coal
Methane emission rate	2–5 m^3/min at the longwall face
Maximum mining level	+710 m
Maximum cover depth	200 m
Mine access	Main incline, auxiliary incline and ventilation incline

Mining operations are initially planned to commence in the C1 seam and progress toward the maximum mining horizon of +710 m, corresponding to an overburden depth of approximately 200 m. The relatively uniform geological conditions across the deposit provide favorable conditions for the application of mechanized retreat longwall mining. The three inclined entries - the main incline, auxiliary incline and ventilation incline - provide access to the subterranean operations and collectively constitute the essential infrastructure for the transport of personnel, conveyance of materials and mine ventilation routes. The mine is a gassy coal mine due to the high methane content (4–15 m^3/t) and methane emission rate (2–5 m³/min) of the coal seams. Sufficient ventilation with careful regulation of the airflow distribution is required to keep the methane concentrations under the legal safety limits during the life of the mine, particularly in the active longwall panels.

III. METHODOLOGY

To provide a clear overview of the research procedure, the overall methodology adopted in this study is summarized in Fig. 2. The proposed framework integrates mine data collection, airflow requirement calculations, ventilation network development, three-dimensional airflow simulation, analytical verification, and main fan selection. The workflow was applied to evaluate the ventilation system during three successive stages of mine development.

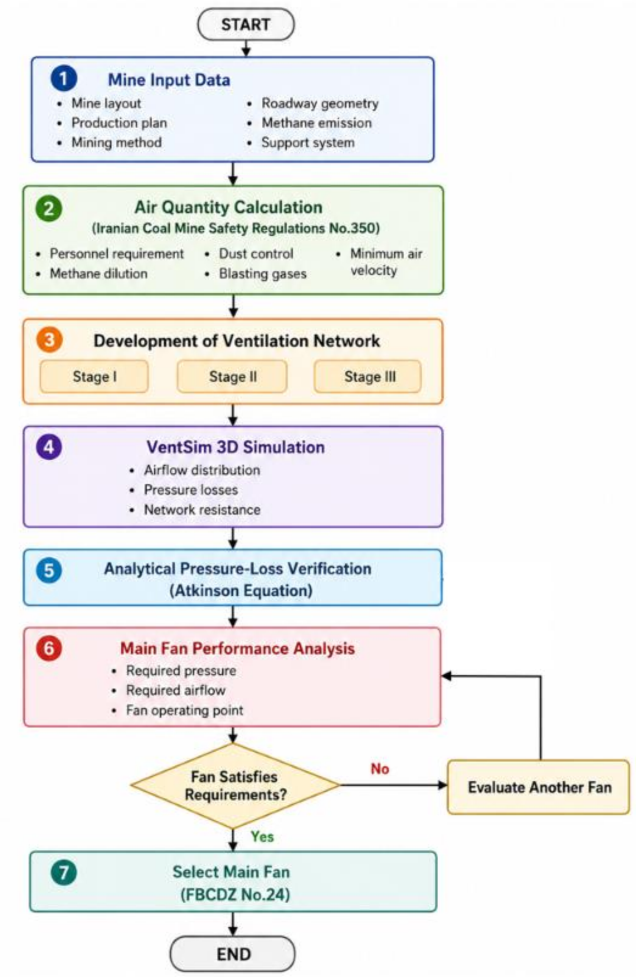


Fig. 2. Flowchart of the proposed methodology for ventilation system design and main fan selection during different mine development stages.

As illustrated in Fig. 2, the study begins with collecting the geological, geometrical, and operational characteristics of the mine. Based on these data, the required airflow is determined according to the Iranian Coal Mine Safety Regulations. Ventilation networks representing the three development stages are then established and analyzed using VentSim. The numerical results are verified through analytical pressure-loss calculations based on the Atkinson equation. Finally, the required operating conditions are compared with the fan performance characteristics to determine the most suitable main fan configuration for each stage of mine development.

A. *Determination of Required Airflow*

The required airflow for both development headings and mechanized longwall panels was determined in accordance with the Iranian Coal Mine Safety Regulations (Publication No. 350). These regulations require that ventilation design satisfies multiple operational constraints, including personnel requirements, dust dilution, blasting fume removal, methane dilution, and maximum allowable air velocity. For each working area, the governing airflow was selected as the maximum value obtained from these criteria, subsequently adjusted using the prescribed safety factors.

1) *Development headings*

For development headings, airflow requirements were evaluated based on personnel demand, dust control, and blasting gas dilution, in accordance with Publication No. 350.

The personnel-based airflow requirement was determined assuming a maximum of five workers per heading. Using the minimum requirement of 6 m^3/min per person:

$$Q_1 = 6n = 30\ m^3/min \tag{1}$$

The dust dilution requirement was calculated based on the maximum excavation cross-sectional area of 15.8 m^2:

$$Q_2 = 0.25 \times 60 \times 15.8 = 237\ m^3/min \tag{2}$$

The airflow required for dilution of blasting gases was calculated considering 30 kg of explosives per blasting cycle and a ventilation time of 60 min,

$$Q_3 = \frac{500 \times 30}{60} = 250\ m^3/min \tag{3}$$

According to Publication No. 350, the design airflow is obtained by applying a safety factor of 1.25 to the governing (maximum) value:

Therefore,

$$Q_H = 1.25 \times \max(Q_1, Q_2, Q_3) = 312.5\ m^3/min \approx 5.2\ m^3/s \tag{4}$$

Therefore, a design airflow of 5.2 m^3/s was assigned to each development heading in the ventilation network model.

2) *Mechanized longwall panels*

For mechanized longwall panels, airflow requirements were assessed based on personnel needs, dust dilution, methane emission control, and maximum permissible air velocity, following Publication No. 350. The airflow required for personnel was

$$Q_1 = 6n = 30\ \mathrm{m^3/min} \quad (5)$$

Dust dilution requirement was calculated using a panel cross-sectional area of 3.3 $\mathrm{m^2}$:

$$Q_2 = 0.25 \times 60 \times 3.3 = 49.5\ \mathrm{m^3/min} \quad (6)$$

Methane emission was estimated based on production rate and gas content of the seam. Considering an annual production of 375,000 t, 280 working days per year, two shifts per day, and 6 productive hours per shift, the resulting coal production rate is:

$$w = 1.86\ \mathrm{t/min} \quad (7)$$

Table 3 presents the gas content of the coal seams at different mining depths.

Table 3. Relationship between gas content and depth

Average gas content ($\mathrm{m^3/t}$)		Maximum gas content ($\mathrm{m^3/t}$)		Depth (m)
Coal seam	Coal seam	Coal seam	Coal seam	
B1,B2	C1,C2	B1,B2	C1,C2	
10.27	9.23	12.65	11.44	100
14.8	13.63	18.78	16.91	200
17.54	15.24	21.19	19.21	300
19.67	17.68	21.48	21.17	400

Taking into account the maximum mining depth of 300 m and measured gas content of the seam, and assuming that approximately 40% of methane is released during the extraction process, the design methane emission factor was taken as 8.5 $\mathrm{m^3/t}$.

Based on Publication No. 350 and a maximum allowable methane concentration of 1%, the required airflow for gas dilution is:

$$Q_4 = 100 \times 1.86 \times 8.5 = 1581\ \mathrm{m^3/min} \quad (8)$$

The maximum allowable airflow based on air velocity constraint (4 m/s) is:

$$Q_{\max} = 4 \times 60 \times 3.3 = 792\ \mathrm{m^3/min} \quad (9)$$

The governing design airflow is therefore:

$$Q_W = 1.25 \times \max(Q_1, Q_2, Q_4) = 1976\ \mathrm{m^3/min} \quad (10)$$

Since

$$Q_W > Q_{\max} \quad (11)$$

the final design airflow was limited to

$$Q_W = 792\ \mathrm{m^3/min} = 13.2\ \mathrm{m^3/s} \quad (12)$$

Accordingly, an airflow of 13.2 $\mathrm{m^3/s}$ was assigned to each longwall panel in the ventilation model.

3) *Total Airflow*

To establish the overall ventilation configuration of Block 3 in the Parvadeh 4 underground coal mine, detailed underground survey data were used to map the main ventilation circuits, auxiliary entries, and secondary airflow routes.

The key ventilation characteristics of the system are summarized as follows:

- Number of development headings: 5
- Number of longwall faces: 2
- Airflow requirement per heading: 6 $\mathrm{m^3/s}$
- Airflow requirement per longwall face: 13.2 $\mathrm{m^3/s}$

To account for leakage and operational uncertainties, a leakage factor of 1.3 and a safety factor of 1.2 were applied. Accordingly, the total airflow demand was estimated using Equation 13:

$$Q_t = (2 \times 13.2 + 5 \times 6) \times 1.3 \times 1.2 = 89.232\ \mathrm{m^3/s} \quad (13)$$

This value represents the initial design capacity of the main ventilation system and serves as the baseline for ventilation modeling and fan selection.

B. *Ventilation Network Modelling and Pressure Loss Calculation*

Ventilation simulations were conducted to identify the optimal fan configuration required to support mine operations over a 15-year production horizon under worst-case resistance conditions, including maximum expected pressure losses in the system.

Three representative development stages were considered:

- Stage I (0–5 years): Initial production and infrastructure development
- Stage II (5–10 years): Intermediate expansion with additional working panels
- Stage III (>10 years): Deep mining and full-scale production phase

For each stage, the ventilation network was modeled based on the actual mine layout and subsequently converted into a three-dimensional (3D) numerical representation. The resulting airflow networks and airway lengths are illustrated in Fig. 3(a–c).

Geometric characteristics of the main roadways, including cross-sectional area, perimeter, and support systems, were incorporated into the model to ensure realistic airflow representation. Frictional pressure losses were calculated using standard Atkinson-type friction factors under steady-state conditions.

To ensure numerical stability and consistency, smooth airflow transition conditions were assumed at bends, with sufficient curvature radius to minimize local turbulence effects. These conditions were used as the reference case for all comparative simulations across the different development stages.

Table 4 summarizes the input parameters used for frictional pressure loss calculations, which form the basis for evaluating pressure distribution and system performance across all stages of mine development. The Atkinson friction factors adopted in this study were selected according to the National Coal Mine Safety Administration of China (NCMSAC, 2022).

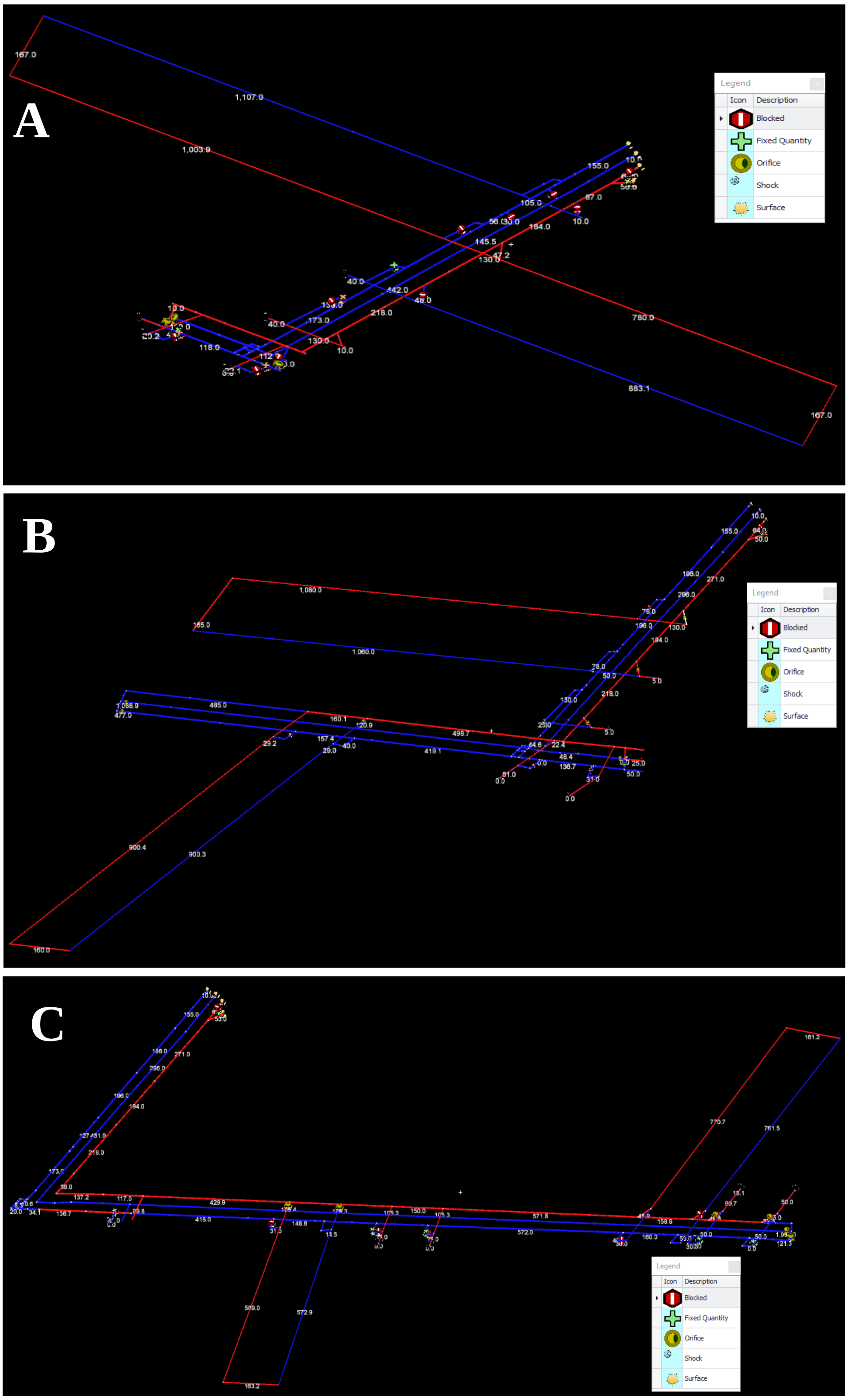


Fig. 3. Schematic representation of the ventilation network of the mine showing airway configurations and lengths during (a) Stage I, (b) Stage II, and (c) Stage III development phases

Table 4. Input parameters for calculating frictional pressure losses in Block 3 of the Parvadeh 4 coal mine

Perimeter (m)	Cross-sectional area (m^2)	Friction factor (kg/m^3)	Support system	Airway type
13.8	12.9	0.0012	Mesh, bolts, shotcrete	Main intake airway
15.3	15.8	0.0012	Mesh, bolts, shotcrete	Auxiliary intake airway
14	13.6	0.0009	Mesh, bolts, shotcrete	Return airway
13.1	11.8	0.0011	Mesh and bolts	Access drifts
13.1	7.2	0.0026	Mesh and bolts	Seam-following tunnels
10	4	0.0045	Hydraulic props	Production stopes

C. *Model Verification*

The reliability and accuracy of the developed VentSim model were evaluated by comparing the simulation results with independent analytical calculations based on the Atkinson equation. In this approach, the total pressure loss of the ventilation network was calculated manually, using the geometrical characteristics of airways, the corresponding friction factors, and airflow rates identical to those implemented in the numerical model. The total pressure loss calculated analytically was then compared to the VentSim simulation results for the same boundary conditions. The manual calculation gave a total pressure loss of 680 Pa, and the VentSim model gave a total pressure loss of 692 Pa. This corresponds to a relative deviation of 1.8% which is considered to be negligible for the simulations of mine ventilation network (Table 5). The close agreement between the analytical and numerical results demonstrates a high level of consistency in the modeling approach. It confirms the reliability of the VentSim-based ventilation network for further airflow distribution analysis and main fan selection.

Table 5. Verification of the VentSim model using analytical calculations

Parameter	Manual calculation	VentSim	Difference (%)
Total pressure loss (Pa)	680	692	1.8

IV. RESULTS

Ventilation simulation software was employed to model and balance the airflow network of Block 3 in the Parvadeh 4 coal mine. Considering the mine's geometric and operational parameters, the airflow distribution was iteratively adjusted until the required airflow rates were achieved at all active working faces. The resulting airflow patterns for the three development stages are presented in Fig. 4, which illustrates air distribution throughout the primary and secondary ventilation networks. The corresponding frictional pressure losses along the main airways are shown in Fig. 5, and the total pressure requirement ($\boldsymbol{\Delta P}$)to be overcome by the main ventilation fan is presented in Fig. 6 to ensure safe and stable mine operation.

The frictional pressure losses computed by the simulation represent the resistance generated by airflow interaction with airway surfaces and structural components of the ventilation network. In accordance with Iranian Standard Publication No. 350, an additional 15% correction factor was applied to account for shock losses, losses due to bends and obstructions, and minor aerodynamic disturbances within the system. After applying this correction, the total pressure loss (ΔP_t) for each development stage was obtained as follows:

Stage I: ΔP_{t1} = 691.5 × 1.15 =795.225 Pa (14)

Stage II: ΔP_{t2} = 897.5 × 1.15 =1032.125 Pa (15)

Stage III: ΔP_{t3} = 1642.4 × 1.15 =1868.06 Pa (16)

The design airflow capacity of the main fan was defined as 20% higher than the total required airflow demand to provide additional operational flexibility for future production variations and long-term mine development scenarios. Accordingly:

$$Q_f = 1.2Q_t = 107.08\,\mathrm{m^3/s}$$

The corresponding fan pressure requirements for each development stage were calculated. In accordance with the Iranian Coal Mine Safety Regulations Publication No. 350, a pressure correction factor of 1.11 was applied to the calculated total mine pressure drop to account for additional pressure losses and provide an adequate safety margin for main fan selection.

$$P_{f1} = 1.11 \times \Delta P_{t1} = 882.7\,\mathrm{Pa} \quad (17)$$

$$P_{f2} = 1.11 \times \Delta P_{t2} = 1145.66\,\mathrm{Pa} \quad (18)$$

$$P_{f3} = 1.11 \times \Delta P_{t3} = 2073.55\,\mathrm{Pa} \quad (19)$$

These results establish the operating range for selecting an appropriate main ventilation fan throughout the life of the mine.

A comprehensive evaluation of available fan models was then conducted based on their performance characteristics, including pressure–volume curves, efficiency curves, and power consumption behaviour. Among the evaluated options, the FBCDZ No. 24 axial fan was identified as the most suitable main ventilation fan for the mine.

The selected fan is equipped with dual 220 kW motors, providing operational flexibility to accommodate varying ventilation demands across different development stages.

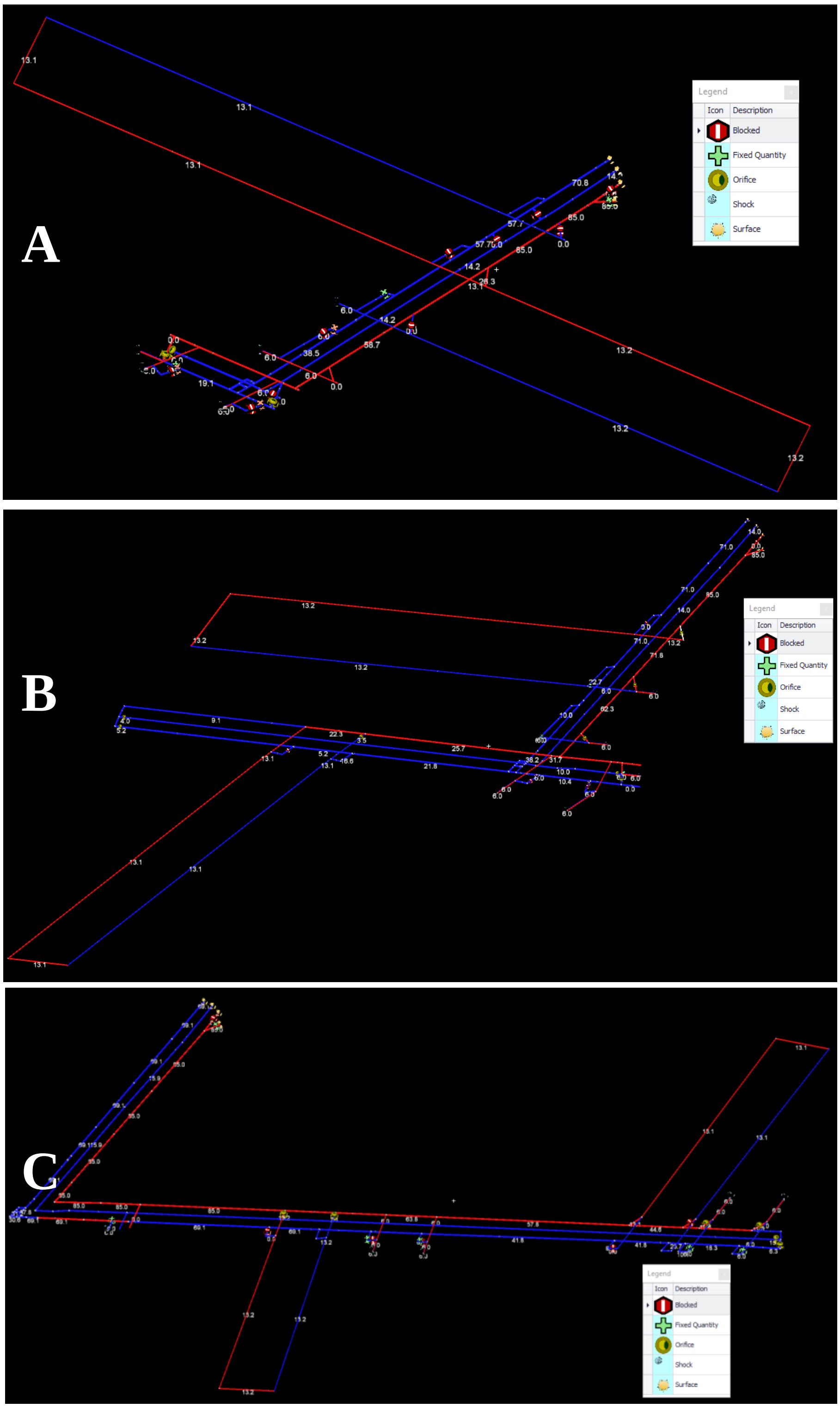


Fig. 4. Distribution of calculated airflow rates across all branches of the ventilation network for the (a) first, (b) second, and (c) third development stages.

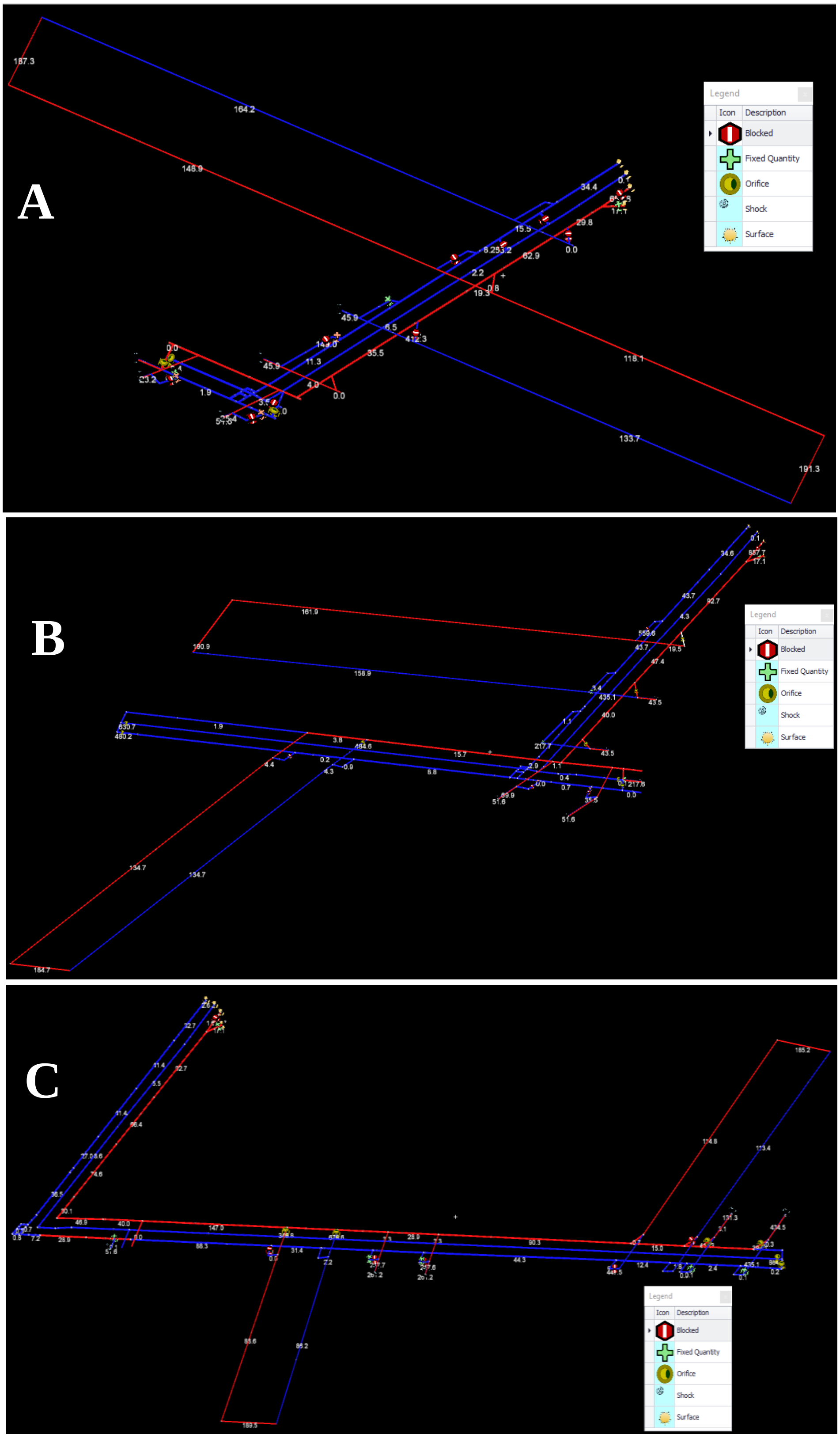


Fig. 5. Frictional pressure losses determined for all airways in the ventilation system during the (a) first, (b) second, and (c) third stages of mine operation.

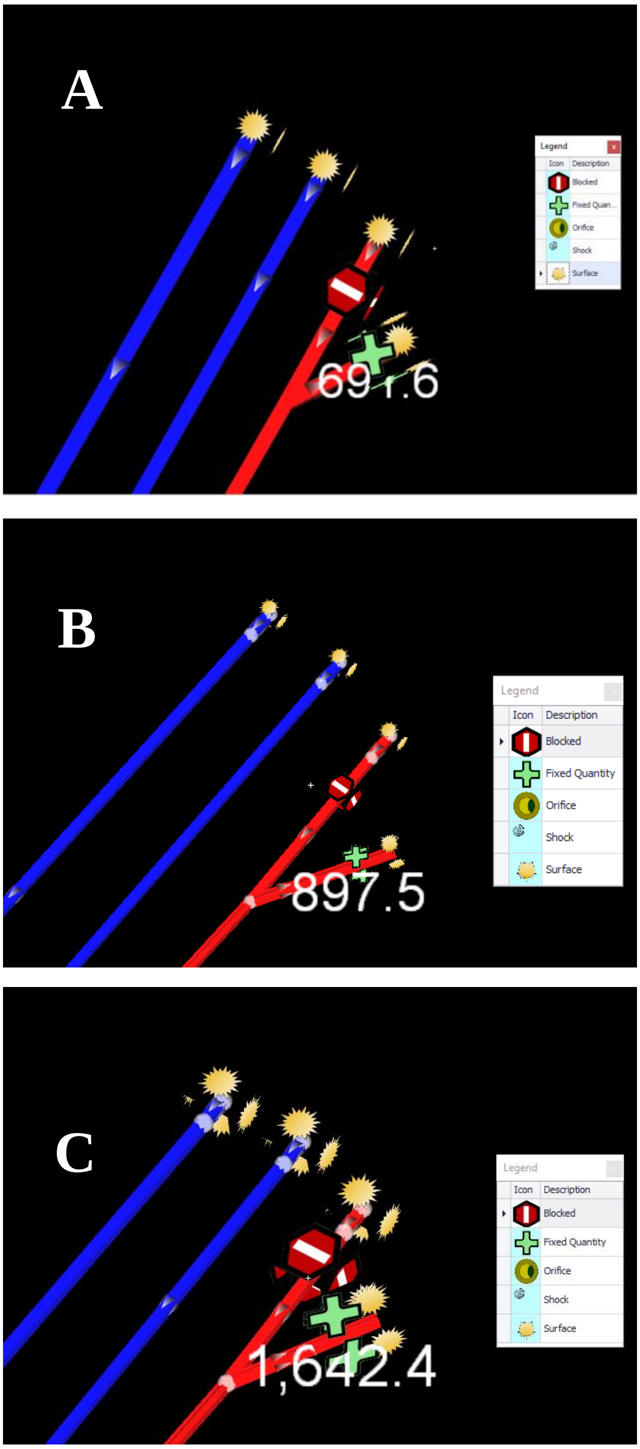


Fig. 6. Total pressure requirement of the main ventilation fan, as computed for the (a) first, (b) second, and (c) third operational stages of the mine.

The performance of the selected fan was further assessed by superimposing the simulated operating points on the manufacturer's characteristic curves for both single- and dual-motor configurations (Fig. 7). The operating points corresponding to Stages I, II, and III are denoted as M1, M2, and M3, respectively.

During Stages I and II, the operating points (M1 and M2) are located within the high-efficiency region of the single-motor performance curve, close to the 80% efficiency contour (Fig. 7a). Under these conditions, the fan is subjected to a relatively low pressure demand and remains well within the stable operating range, far from the surge and overload regions. This operating condition ensures stable performance and provides sufficient safety margin to accommodate moderate increases in system resistance.

As the mine develops beyond the tenth year, the ventilation network increases, increasing the general resistance of the airways and, consequently, the fan pressure. Under these conditions, one motor operation cannot provide the required airflow, so two-motor operation is needed. As shown in Fig. 7b, the operating point (M3) falls within the high-efficiency region of the dual-motor characteristic curve, where the fan operates at an efficiency of approximately 80–85%. Under this operating condition, the fan delivers approximately 107 m^3/s of air, which meets the mine ventilation requirement.

The movement of the operating point from M1 to M3 is primarily associated with the gradual increase in ventilation resistance as the mine expands. Although both the required pressure and airflow increase during later development stages, the operating points remain within the recommended range of the FBCDZ No. 24 fan. This indicates that the selected fan is suitable for all three development stages of the mine. The dual-motor mode is required only in the final stage, whereas a single motor is sufficient during the earlier stages.

V. Discussion

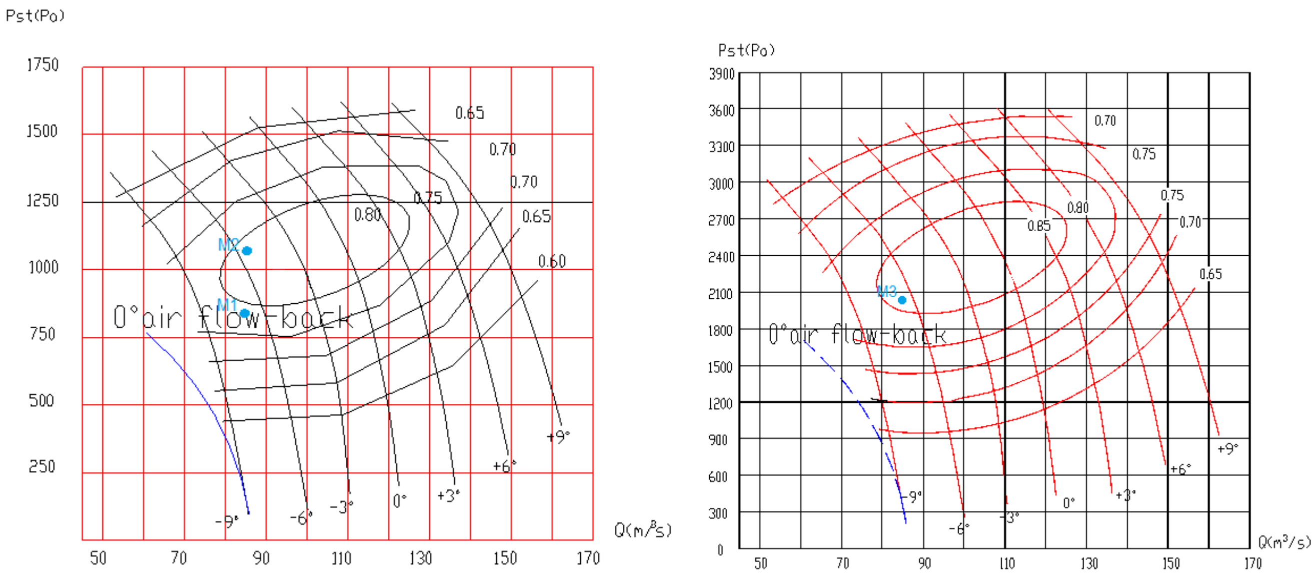
The simulation results show that ventilation conditions within Block 3 develop gradually as mining progresses. During the initial phase of development, the ventilation network is relatively short and offers low resistance to airflow. With the advancement of the mine, the main intake and return airways grow longer and new connections are made to the network. These changes lead to an increase in the overall airway resistance and consequently, the pressure needed from the main ventilation fan. The Atkinson equation suggests that this increase is primarily dictated by airway length and frictional resistance. Therefore, the total pressure loss rises from about 796 Pa in Stage I to 1868 Pa in Stage III. The required airflow remains almost unchanged because it is determined by the production plan and the ventilation requirements of the active longwall panels and development headings. However, the higher resistance causes the operating point of the fan to move toward a higher-pressure region of the performance curve. For the first two development stages, the required operating point is achieved with a single motor while maintaining satisfactory fan efficiency. Under these conditions, the pressure demand is relatively low, resulting in lower power consumption and simpler fan operation. For the final stage, the elevated aerodynamic resistance of the network demands the activation of the dual-motor configuration. This operational adjustment is strictly governed by the higher pressure requirements of the expanded network, while the design airflow volume remains constant. The dual-motor configuration is able to supply approximately 107 m^3/s at the required operating pressure, while the operating point remains within the recommended efficiency range of the fan. These results indicate that the selected FBCDZ No. 24 fan is suitable for all planned stages of mine development and can satisfy the ventilation requirements over the entire 15-year production period without replacing the main fan.

Overall, the results highlight the importance of integrating long-term mine planning into ventilation system design. A fan selected solely based on initial development conditions would not be capable of meeting the requirements of later mining stages without significant modification or replacement. Therefore, coupling three-dimensional ventilation simulation with staged mine development scenarios provides a more robust and reliable framework for main fan selection and system optimization over the full mine life.

VI. CONCLUSION

This study developed an integrated methodology for the design and optimization of the ventilation system in Block 3 of the Parvadeh 4 coal mine by coupling ventilation network analysis with three-dimensional airflow simulation. The approach was applied to evaluate airflow requirements, pressure losses, and main fan performance across different stages of mine development. The results indicate that the required airflow for development headings and mechanized longwall panels is 5.2 m^3/s and 13.2 m^3/s, respectively, in accordance with the Iranian Coal Mine Safety Regulations (Publication No. 350). Ventilation network simulations revealed a progressive increase in total pressure requirement from 795 Pa in Stage I to 1032 Pa in Stage II and 1868 Pa in Stage III. This increase is primarily attributed to the expansion of airway length and the associated growth in network resistance as mining advances. The required capacity of the main ventilation fan was estimated at approximately 107 m^3/s, including a 20% design allowance to accommodate future mine development and possible variations in operating conditions. During the first and second development stages, the required airflow and pressure can be provided by operating a single motor, with the operating points remaining within the efficient region of the fan performance curve. As mining advances to Stage III, the increase in ventilation resistance requires both motors to be operated in order to maintain the required airflow and pressure. The analysis indicates that the FBCDZ No. 24 twin-motor axial fan is capable of supplying the ventilation requirements for all three development stages considered in this study. The fan provides sufficient pressure capacity for the planned 15-year mine life without requiring replacement under the assumed mining conditions.

The procedure presented in this study combines airflow calculations, ventilation network analysis, and fan performance evaluation within a single design process. Although the methodology was developed for Block 3 of the Parvadeh 4 coal mine, the same approach can be adopted in other underground coal mines where ventilation requirements change as mine development progresses.



(a) (b)

Fig. 7. Characteristic performance curves of the main fan under single- and dual-motor configurations (a and b, respectively).

AUTHOR CONTRIBUTIONS

Both authors contributed to the study: Mohsen Safari—conceptualization, methodology, investigations, visualization; Hossein Arasteh—formal analyses; the draft was written by Mohsen Safari and Hossein Arasteh. Both authors read and approved the final manuscript.

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DATA AVAILABILITY

Inquiries about data availability should be directed to the authors. Data will be supplied upon request.

DECLARATIONS CONFLICT OF INTERESTS

The authors have no relevant financial or non-financial interests to disclose.

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