Coal dust monitoring and computational simulations of dust dispersion in continuous miner development heading through auxiliary ventilation systems

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Dispersing coal dust to a safe level near the mining face is of utmost importance for maintaining a safe and healthy workplace environment in any mine. The huge amount of coal dust generated during coal winning near a mine development heading is generally dispersed through auxiliary ventilation systems. In this study, dispersion of coal dust in a continuous miner development heading was analysed with five different auxiliary ventilation systems through computational fluid dynamics simulations, and their efficacy of dust dispersal to a safe level was compared. The dust concentration in the heading developed by continuous miner was monitored by a Grimm aerosol spectrometer. The k–ε turbulence model was used to perform 3D computational simulations utilizing real mine data. This study provided an insight into the dispersion behaviour of coal dust in the development heading with diverse auxiliary ventilation systems. The line brattice system proved to be the most effective means of dust dispersion. Nonetheless, better dispersion of coal dust in the development heading was achieved at line brattice distances of 0.75 and 1.0 m from the side wall.

Keywords: Auxiliary ventilation systems, coal dust, computational simulation, development headings, dispersion, line brattice, underground coal mines.

THE day-by-day increase in coal production to meet its high demand has led to a surge in the mechanization level and dust generation in underground coal mines. Moreover, the size of dust particles produced in coal mines has reduced significantly with the deployment of sophisticated coal-cutting machines. The large quantity of dust produced in underground coal mine development headings advanced by continuous miner is a major concern. The airborne coal dust leads to explosion hazards in underground coal mines and causes coal workers' pneumoconiosis (CWP)[1,2]. Due to greater surface area per unit mass, the finer coal dust particles disperse easily in air and remain airborne for a longer period, thereby posing greater explosion there than the coarser particles[3–6]. It has been found that coal dust concentration in the range 100–120 g/m^3 is dangerous for mine workings and most violent explosions occur when the concentration varies in the range 300–400 g/m^3 (ref. 7). From the miners' health point of view, the Coal Mines Regulations in India stipulates the threshold limit for airborne respirable dust concentration in underground working environment[8]. In order to ensure safe mining and healthy workplace environment, proper dust control in underground coal mines is of utmost importance.

Management of large amounts of dust produced in continuous miner development headings with inefficient dust suppression systems is a major challenge for the mine operators. Under this situation, adoption of suitable techniques for effective dust dispersion and control is a recourse. In underground development headings, auxiliary ventilation systems such as forcing, exhaust, combination of forcing and exhaust (overlapping) system and line brattice are commonly used for ventilation and dispersion of dust and mine gases[9]. Yet, each ventilation system has its own merits and limitations for application in different mining conditions. Hence it is imperative to study the efficacy of these ventilation systems to choose the one suitable for a particular situation.

Generally, forcing ventilation system is preferred for ventilating the development headings, as it delivers fresh, cool and dry air near the face. However, the main drawback of the forcing system is that it takes more time to remove the dust and gaseous pollutants from underground mining face. In contrast, the exhaust ventilation system swiftly sucks the dust and gases into the duct near the face and discharges them out of the heading; thus their mixing with the rest of the air is avoided. However, the exhaust system requires the ventilation duct to be extended closer to the development face or a smaller setback distance must be maintained for effective evacuation of the pollutants. The line brattice is commonly used in small-length headings in bord and pillar mining. Though it is cheaper compared to the ducting ventilation systems,

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significant leakage of air through the gaps near the roof and floor takes place in this system[9–11].

Now-a-days, more impetus is given to study airflow and dust dispersion behaviour in underground mine workings and the development face through diverse ventilation systems. Kurnia *et al.*[12] numerically analysed the applications of different auxiliary ventilation systems and found that the line brattice ventilation system causes greater dust dispersion along the development heading. Mishra *et al.*[13] studied the influence of various auxiliary ventilation parameters on dust dispersion through numerical simulations and proposed a suitable combination of parameters. Wei *et al.*[14] concluded that the concentration of coal dust near the mining face may be controlled by increasing the velocity of air. Torano *et al.*[15] found that the concentration of coal dust in underground development heading can be controlled by increasing the velocity of air, varying the height of the ventilation duct from the floor and reducing the setback distance of the ventilation duct from the working face. Kurnia *et al.*[16] evaluated the brattice ventilation system through computational simulations, and observed that half blockage and quarter blockage are less effective in dust dispersion compared to full blockage, and smaller setback distance causes greater dust dispersion in the underground mine face. Tariq and Bekir[17] numerically analysed the effect of length of the line brattice in the development heading with regard to side wall distance on the airflow at the working face. Hargreaves and Lowndes[18] computationally analysed the airflow pattern at various stages of the cutting cycle of the continuous miner with an auxiliary ventilation system and validated the computational results with mine data. Geng *et al.*[19] observed a nonuniform distribution of dust concentration in the mine roadway and significantly higher coal dust concentration near the working face, especially on the exhaust side. Moreover, they observed a decrease in dust concentration in the coal-mine roadway with increase in the velocity of air flow and decrease in the ventilation duct setback distance from the mining face.

In the present study, the dust measurement and computational simulations on influence of various auxiliary ventilation systems on coal-dust dispersion behaviour in a full-scale underground coal mine heading developed by continuous miner have been performed. The objectives of this study are to: (i) examine the dispersion behaviour of coal dust in the underground development heading with different auxiliary ventilation systems, (ii) analyse and compare the efficacy of different auxiliary ventilation systems for identifying the best system dispersing dust to a safe level, and (iii) study the effect of variation of line brattice distance from the side wall of the development heading on dust dispersion and determine the ideal distance causing greater dust dispersion. The actual dust monitoring data and mine dimensions were used in the three-dimensional simulations for evaluating the dust dispersion efficacy of the ventilation systems. The outcome of this comparative study will enable the practising mine operators to select the appropriate auxiliary ventilation system for better dust dispersion in underground development headings advanced by continuous miners.

Study area

This study was carried out in the MIC Unit, Jhanjra Project Colliery of Eastern Coalfields Ltd (ECL), West Bengal, India. Figure 1 shows the location of Jhanjra Project Colliery. It is a fully mechanized mine deploying shearer, powered support, armored face conveyor (AFC), continuous miner and shuttle cars for coal extraction. Coal is extracted from the underground mine using both the longwall, and bord and pillar methods of mining in different panels. The annual coal production of the colliery is 3.50 MT, which is the highest production from any underground mine of ECL. The airflow rate, dust concentration and dimensions of the continuous miner development heading in the mine were measured for use in numerical simulations.

Methodology

Coal dust monitoring

The measurement of dust concentration in the underground development heading advanced by the combination of continuous miner and shuttle cars was carried out using a Grimm aerosol spectrometer (model 1.108). The spectrometer works on the principle of light scattering and measures the airborne dust concentration in 16 different size channels varying between >0.23 and >20 μm in the mass concentration range 0.1–100,000 μg/m^3 with a precision of ±3% (refs 20, 21). It can also measure dust concentration in particle counts mode in the range 1–2,000,000 counts/litre, as well as in environmental mode such as PM 10, PM 2.5 and PM 1. It sucks air through the sample inlet located at the front panel at a flow rate of 1.2 litres/min. The spectrometer records dust concentration data at every 6 sec and we have taken the average dust concentration at every 60 sec. Hence the dust concentration measured in this study can be considered as the average concentration. The gravimetric correction factor (C-factor), which depends on the particle shape, density and refractive index of the particles, was used to convert the particle count to mass concentration. According to the instrument manual, we considered the default C-factor value of 1.

Considering the measurement of true representative airborne dust concentration and safety of the operator and instrument, the coal dust concentration was monitored for about 6 min at 6 m distance from the development face during coal cutting by the continuous miner. Figure 2 shows the mean dust concentration of 16 distinct sizes

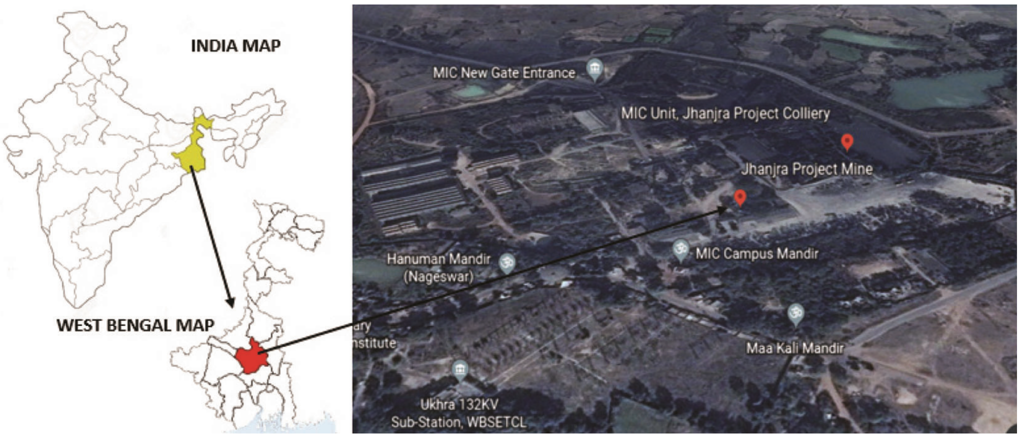
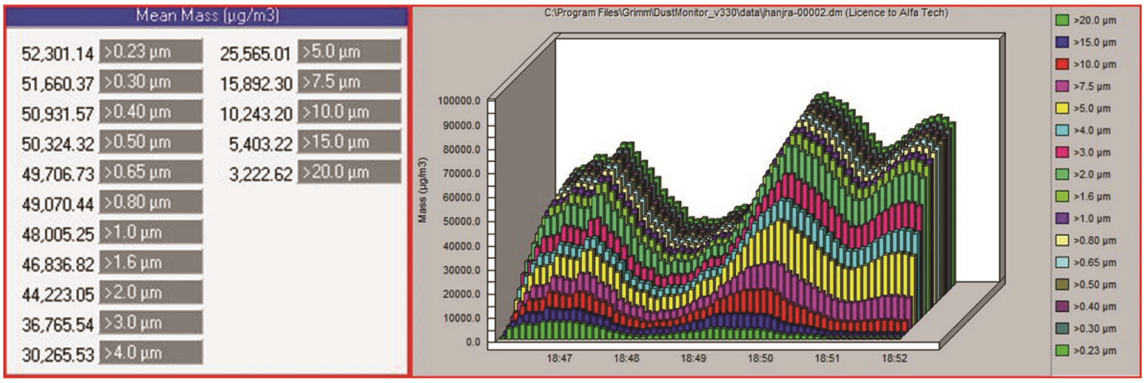


Figure 1. Location of the MIC Unit, Jhanjra Project Colliery, West Bengal, India.


Mean Mass (µg/m3)

52,301.14	>0.23 µm	25,565.01	>5.0 µm
51,660.37	>0.30 µm	15,892.30	>7.5 µm
50,931.57	>0.40 µm	10,243.20	>10.0 µm
50,324.32	>0.50 µm	5,403.22	>15.0 µm
49,706.73	>0.65 µm	3,222.62	>20.0 µm
49,070.44	>0.80 µm		
48,005.25	>1.0 µm		
46,836.82	>1.6 µm		
44,223.05	>2.0 µm		
36,765.54	>3.0 µm		
30,265.53	>4.0 µm		

C:\Program Files\Grimm\DustMonitor_v330\data\jhanjra-00002.dm (Licence to Alfa Tech)

Figure 2. Mean concentration of coal dust in distinct sizes and dust concentration variation with respect to time measured in the underground development heading using the Grimm aerosol spectrometer[13].

Table 1. Auxiliary ventilation parameters

Parameter	Value
Ventilation duct diameter (m)	1
Setback distance of the duct (m)	7
Duct height from the floor (m)	3
Velocity of air in the duct (m/s)	7
Setback distance of the line brattice (m)	7
Variation of line brattice distance from the side wall (m)	0.75 to 2
Airflow through the line brattice (m^3/s)	30

and dust concentration variations with respect to time analysed by the Grimm software. The total (>0.23 µm) and respirable (<5 µm) fractions of dust concentrations were recorded as 52.3 and 26.74 mg/m^3 respectively; they are much larger than the threshold limit stipulated by the Coal Mines Regulation[8]. This suggests the adoption of proper dust control measures in the development heading to bring down the coal dust concentration to a safe level.

Numerical simulations

Computational domain formulation: The 3D computational simulations were conducted using ANSYS CFD software to analyse the dispersion behaviour of coal dust in the underground mine development heading. The rectangular-shaped computational domains of the development heading with five different auxiliary ventilation systems, namely forcing, exhaust, overlapping, line brattice and a combination of line brattice and exhaust system were developed (Figure 3). Dust is produced near the working face during coal cutting by the continuous miner. The mining face is ventilated by air intake through the ventilation duct and line brattice in the different auxiliary ventilation systems. The ventilation duct and line brattice setback distance from the working face was maintained at 7 m. The diameter and height of the duct from the floor were considered as 1 and 3 m respectively. Figures 3 and 4 show the air inlet, air outlet, mining face and important auxiliary ventilation parameters as presented in Table 1. The computational domain of the development heading was meshed by a tetrahedron mesh consisting of about 1.2 million cells.

Boundary conditions and simulations: The two-equation standard $k–\varepsilon$ turbulence model solving the turbulent kinetic energy was chosen for simulations[13]. The $k–\varepsilon$ model permits determination of both timescale and turbulence

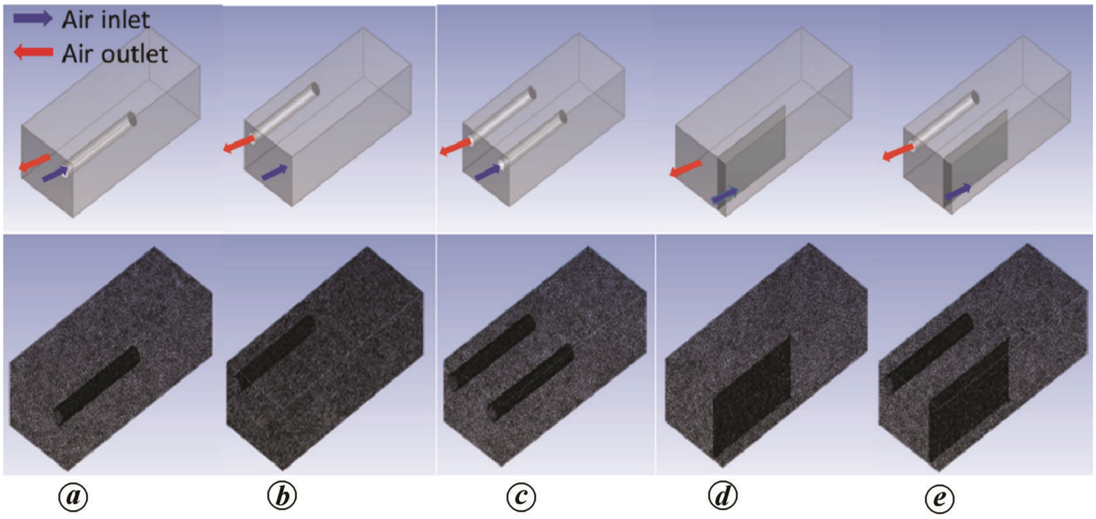


Figure 3. Geometry of computational domain with different ventilation systems: ***a***, forcing; ***b***, exhaust; ***c***, overlapping, ***d***, line brattice; ***e***, line brattice–exhaust combination.

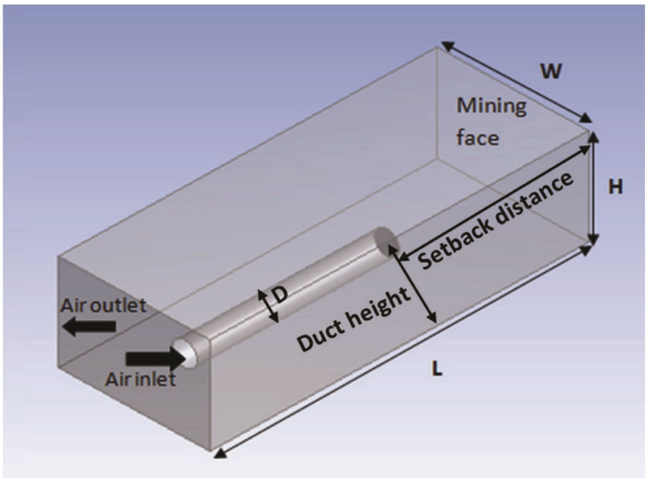


Figure 4. Enlarged view of computational domain: height (H) = 4 m, width (W) = 6 m, length (L) = 15 m, duct diameter (D) = 1 m, duct height = 3 m and setback distance = 7 m (ref. 13).

length by solving two distinct transport equations. The transport equations for turbulence kinetic energy (k) and its rate of dissipation (ε) are given by[22]

$$\frac{\partial}{\partial t}(\rho k)+\frac{\partial}{\partial x_i}(\rho k u_i)=\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right]+G_k-\rho\varepsilon, \tag{1}$$

$$\frac{\partial}{\partial t}(\rho\varepsilon)+\frac{\partial}{\partial x_i}(\rho\varepsilon u_i)=\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial\varepsilon}{\partial x_j}\right]$$

$$+C_{1\varepsilon}\frac{\varepsilon G_k}{k}-C_{2\varepsilon}\rho\frac{\varepsilon^2}{k}, \tag{2}$$

where σ_k and σ_ε are turbulent Prandtl numbers for k and ε respectively, G_k represents generation of turbulence kinetic energy due to mean velocity gradient and $C_{1\varepsilon}$ and $C_{2\varepsilon}$ are constants. The turbulence viscosity μ_t is given by

$$\mu_t=\rho C_\mu\frac{k^2}{\varepsilon}, \tag{3}$$

where C_μ is a constant and σ_k, σ_ε, C_μ, $C_{1\varepsilon}$ and $C_{2\varepsilon}$ are 1, 1.3, 0.09, 1.44 and 1.92 respectively.

The coal dust produced from the underground mine face was presumed to be spherical in shape and considered as the discrete phase. The movement of the dust particles was considered utilizing discrete phase model (DPM), which allows coupling between phases and its impact on both the continuous phase flow and discrete phase trajectories. The model also computes the particle trajectories for every moment of the discrete phase.

The Rosin–Rammler diameter distribution was considered with dust-diameter range between 0.23×10^{-6} and 1×10^{-4} m. The Rosin–Rammler diameter distribution is a convenient representation of dust-size distribution, wherein the whole size ranges are separated into appropriate number of discrete intervals. Each discrete interval is represented by the mean diameter for which the trajectory calculations are performed. The Rosin–Rammler distribution function (Y_d) is based on the assumption of exponential relationship between dust diameter (d) and dust mass fraction with diameter greater than d (ref. 23).

$$Y_d=\mathrm{e}^{-(d/d_m)^n}, \tag{4}$$

where n and d_m are the spread parameter and mean diameter respectively.

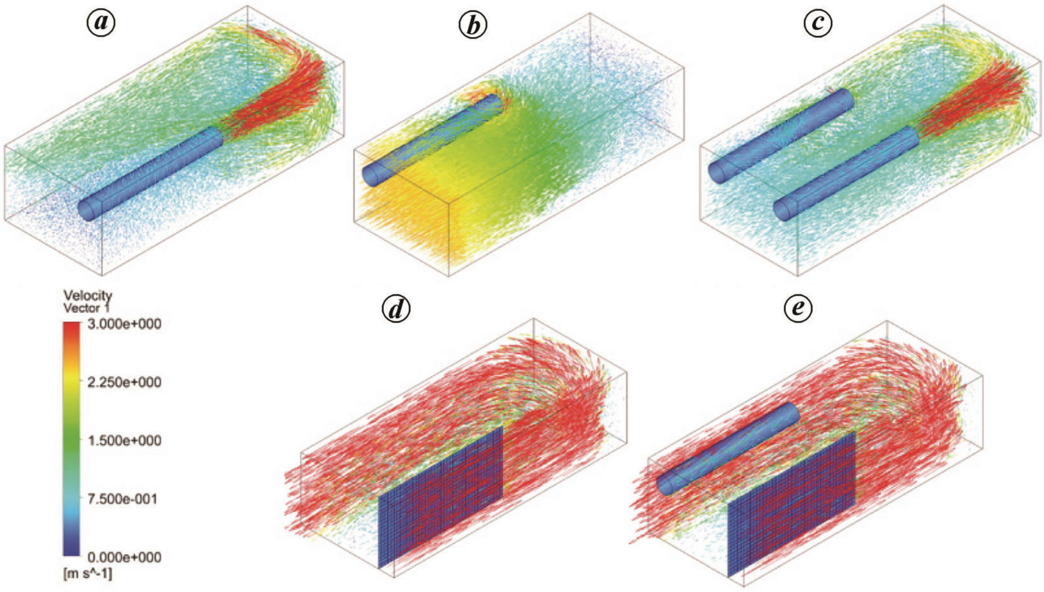


Figure 5. Air velocity vectors showing variation of air velocity inside the development heading in different auxiliary ventilation systems. ***a***, Forcing; ***b***, Exhaust; ***c***, Overlapping; ***d***, Line brattice; ***e***, Line brattice–exhaust combination.

The density of coal dust and air was considered as 1390 and 1.224 kg/m^3 respectively. The total dust generation rate near the mine working face was determined using the following formula[14]

$$\text{Total dust generation rate (kg/s)} = cvA, \tag{5}$$

where c, v and A represents the dust concentration (kg/m^3), velocity of air (m/s) and cross-sectional area of the development heading (m^2) respectively. Air velocity of 2.5 m/s measured at the development heading inlet was used and standard atmospheric pressure was considered as the outlet pressure. The stream-wise temperature gradient was set to zero. The cross-sectional area of the development heading was measured to be 24 sq. m. From the measured dust concentration value of 52.3 mg/m^3, the total dust generation rate near the mining face was calculated as 0.00314 kg/s using eq. (5) and used in the simulations. Table 1 presents the auxiliary ventilation parameters considered in the simulations. The simulations converged after 5000–7000 iterations and took about 8–10 h for convergence.

Results and discussion

Effects of auxiliary ventilation systems on dust dispersion

Dispersion of dust generated near the mining face in the underground development heading takes place with air current. A previous study reported better dust dispersion at 7 m/s air velocity in 1 m duct diameter at a setback distance of 7 m from the development face[13]. Hence these air velocity, setback distance and duct diameter values were considered in the present study. The auxiliary ventilation parameters considered in the simulations are presented in Table 1. However, for comparison of the ventilation systems, the line brattice distance from the side wall was taken as 1 m.

The air velocity vectors shown in Figure 5 depict the variation of air movement along the development heading in different auxiliary ventilation systems. From the figure, it may be observed that air stagnation or dead zones with negligible air velocity are formed near the corners and face of the development heading in case of the forcing, exhaust and overlapping systems. However, in case of the line brattice and a combination of line brattice and exhaust ventilation systems, the distribution of air velocity is found to be more or less uniform throughout the heading.

The air velocity and dust concentration contours at 2 m intervals from the development face are shown in Figures 6 and 7 respectively. Figure 6 clearly shows the air stagnation zones in blue colour near the corners and face of the development heading in case of the forcing, exhaust and overlapping systems. Figure 7 also shows the accumulation of coal dust close to the corners of the development heading due to formation of air stagnation zones.

The efficacy of dust dispersion from a mining face in the underground development heading is significantly affected by the type of auxiliary ventilation system used. Figure 8 shows the variation of coal dust concentration along the development heading with different auxiliary ventilation systems. Generally, the dust concentration decreased significantly from the development face up to a

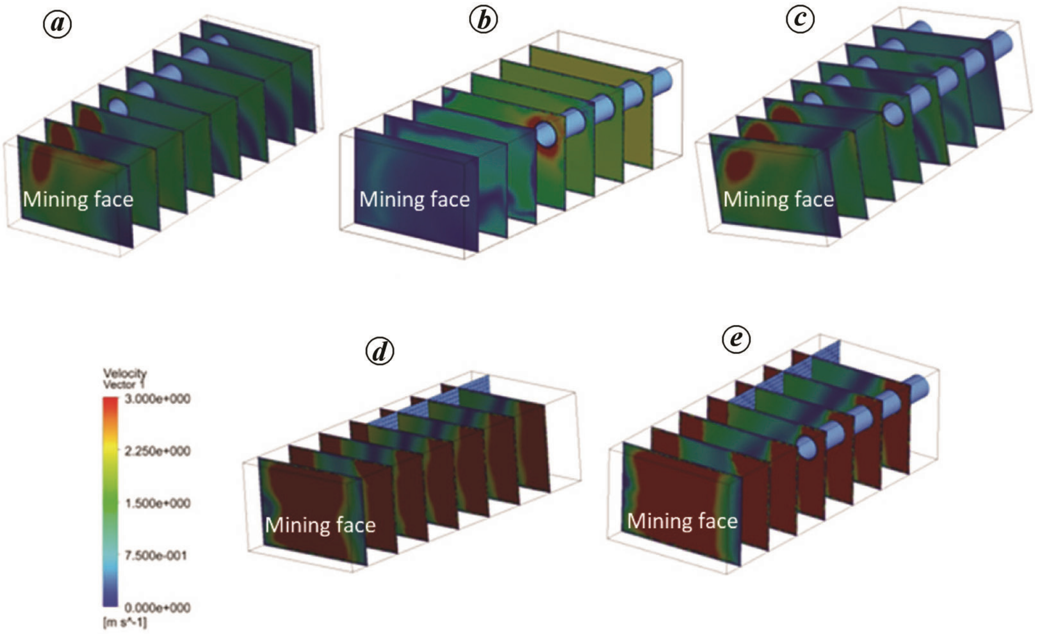


Figure 6. Air velocity contours at 2 m intervals from the mining face in distinct auxiliary ventilation systems: ***a***, forcing; ***b***, exhaust; ***c***, overlapping; ***d***, line brattice; ***e***, line brattice–exhaust combination.

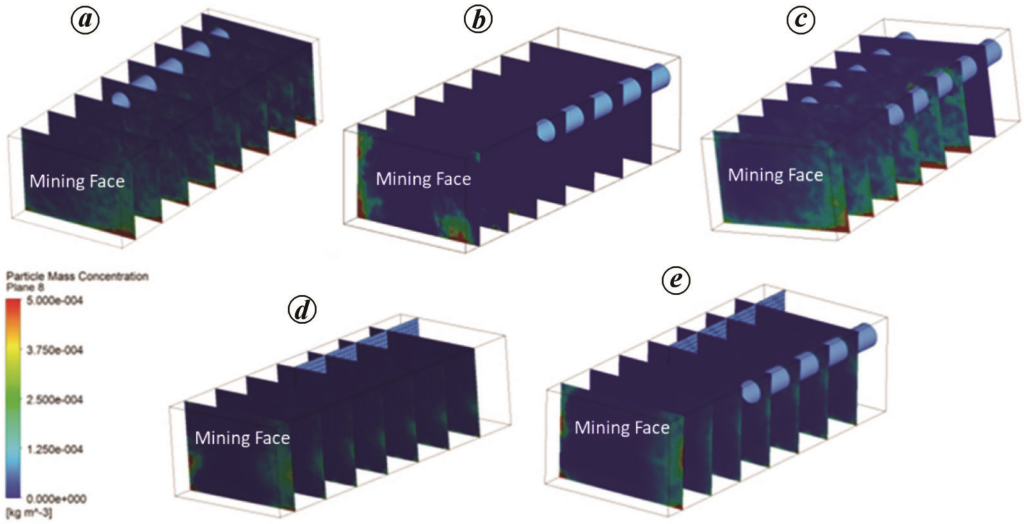


Figure 7. Dust concentration contours at 2 m intervals from the mining face in distinct auxiliary ventilation systems: ***a***, forcing; ***b***, exhaust; ***c***, overlapping; ***d***, line brattice; ***e***, line brattice–exhaust combination.

distance of 5 m and stabilized thereafter, except in the forcing and overlapping systems, wherein the dust concentration slightly increased after 5 m. The concentration of coal dust at 2 m distance from the development face in forcing, exhaust, overlapping, line brattice and line brattice–exhaust combination was found to be 64.5, 31.5, 44.5, 15.9 and 18.0 mg/m^3 respectively. However, at 5 m distance from the development face, the concentrations of coal dust was 48.2, 21.3, 36.5, 6.43 and 5.73 mg/m^3 respectively. This indicates that among all the ventilation systems, both the line brattice and line brattice–exhaust combination are effective in dispersing dust from the working face. However, since there is a marginal difference between the dust concentrations recorded in these two systems, and the line brattice–exhaust combination requires the use of additional exhaust fan and power for its operation, the line brattice system alone is preferred. However, one major drawback of this system is that it reduces the effective working width of the heading and thereby poses operational difficulties for mechanized coal cutting, particularly if the gallery width is small or the line brattice distance from the side wall is large. Hence, in this study, the line brattice distance from the side wall was considered to be 1 m to avoid the operational difficulties of the continuous miner and shuttle car in the 6 m wide development heading.

In the exhaust ventilation system, dust concentration near the mining face, especially within 1 m, was found to be significantly higher (varying in the range 90–1602 mg/m^3) compared to other ventilation systems. This is due to greater setback distance of the duct from the face (7 m), leading to inefficient evacuation of dust generated near the face. This suggests that a small setback distance between the working face and duct of the exhaust ventilation system should be maintained for effective dust evacuation and minimizing dust concentration near the face[10]. Beyond 8 m from the face, the concentration of coal dust throughout the development heading was observed to be the lowest in the exhaust ventilation systems. This is due to complete discharging of dust from the development heading through the ventilation duct without any intermixing.

Variations of coal dust concentration along the development heading in case of forcing and overlapping systems follow more or less a similar trend, except for a few anomalies. Overall, the dust concentration in case of overlapping system was slightly higher than the forcing system, though it utilizes the advantages of both the forcing and exhaust ventilation systems. The sudden increase in dust concentration observed between 5.5 and 7.5 m in case of the overlapping system was due to recirculation of air close to the delivery end of the ventilation duct located 7 m away from the mining face. In the forcing system, after an initial decrease up to a distance of 5 m from the face, the dust concentration increased and thereafter stabilized with a higher concentration level in the remaining part of the heading. Despite this limitation, the forcing system has the advantage that it delivers fresh and dry air to the mining face.

Effect of line brattice distance from the side wall

The brattice ventilation system is one of the best auxiliary ventilation systems for small length headings. However, the distance of the line brattice from the side wall is the most important parameter affecting dust dispersion in the development heading. Computational simulations were performed by varying the line brattice distance from the side wall of the development heading at 0.75, 1, 1.5 and 2 m, to determine the ideal distance causing greater dust dispersion. In this study, half of the total quantity of air flowing in the main gallery, i.e. 30 m^3/s, is coursed to ventilate the development heading. The air velocity vectors shown in Figure 9 depict the variation of air velocity along the development heading at different line brattice distances from the side wall. It may be observed that a greater amount of air reaches near the working face at line brattice distances of 0.75 and 1.0 m from the wall compared to other distances. However, at a line brattice distance of 2 m, the amount of air reaching near the heading is observed to be inadequate for causing better dust dispersion.

The air velocity and dust concentration contours at 2 m intervals from the development face are shown in Figures 10 and 11 respectively. These contours indicate the effect of variation of line brattice distance from the side wall on the air velocity and dust concentration in the development heading. From these contours it can be observed that the air velocity decreases and dust concentration increases with increase in the line brattice distance from the side wall at a particular airflow rate. The air velocity reaching the mining face is the highest at line brattice distance of 0.75 m followed by at 1.0 m, thereby resulting in efficient dust dispersion in the development heading.

Figure 12 shows the variations of mean dust concentration along the development heading at various line brattice distances from the side wall. The concentration of coal dust at 2 m distance from the working face at line brattice distances of 0.75, 1, 1.5 and 2 m was found to be 11.8, 15.9, 57.7 and 85.7 mg/m^3 respectively. However, at 5 m from the face, the concentration was found to be 7.31, 6.43, 16.3 and 16.7 mg/m^3 respectively, which decreased significantly thereafter. The dust concentration more or less stabilized beyond 5 m distance from the mining face. The concentration along the development heading was recorded lowest at the line brattice distance of 0.75 m because of better dust dispersion. In contrast, the concentration of coal dust along the development heading was observed to be highest at 2 m line brattice distance due to lower air velocity resulting in poor dust dispersion. This is because the air velocity along the development heading correspondingly decreases with increase

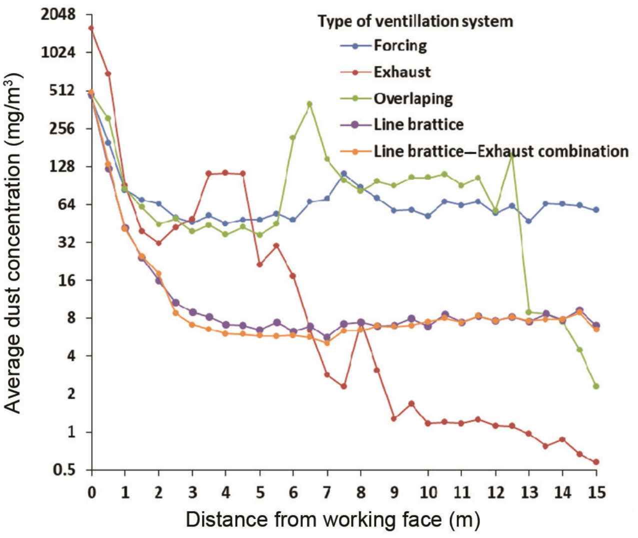


Figure 8. Variation of dust concentration throughout the development heading in distinct auxiliary ventilation systems.

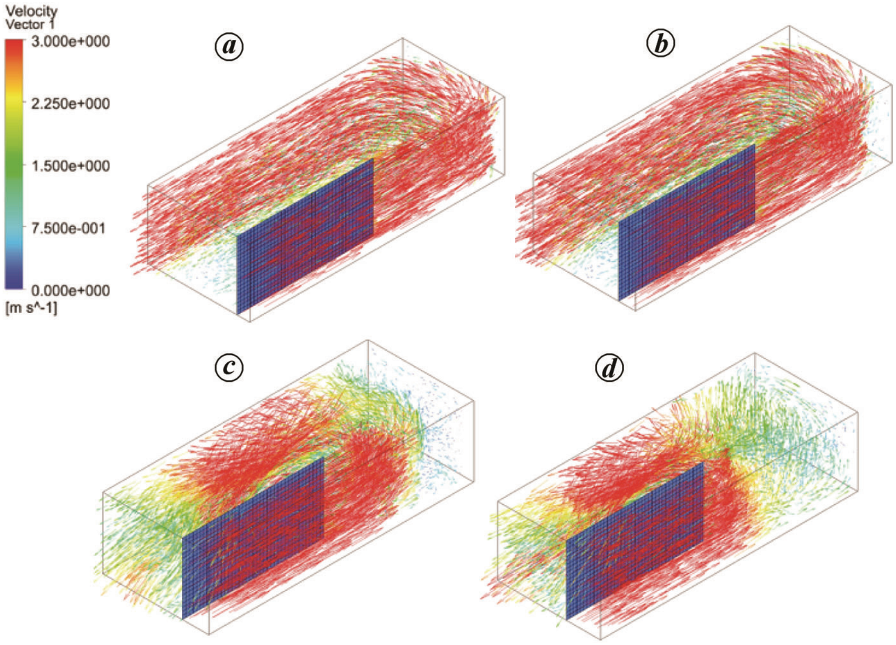


Figure 9. Air velocity vectors in the development heading at different line brattice distances from the side wall: ***a***, 0.75; ***b***, 1; ***c***, 1.5; ***d***, 2 m.

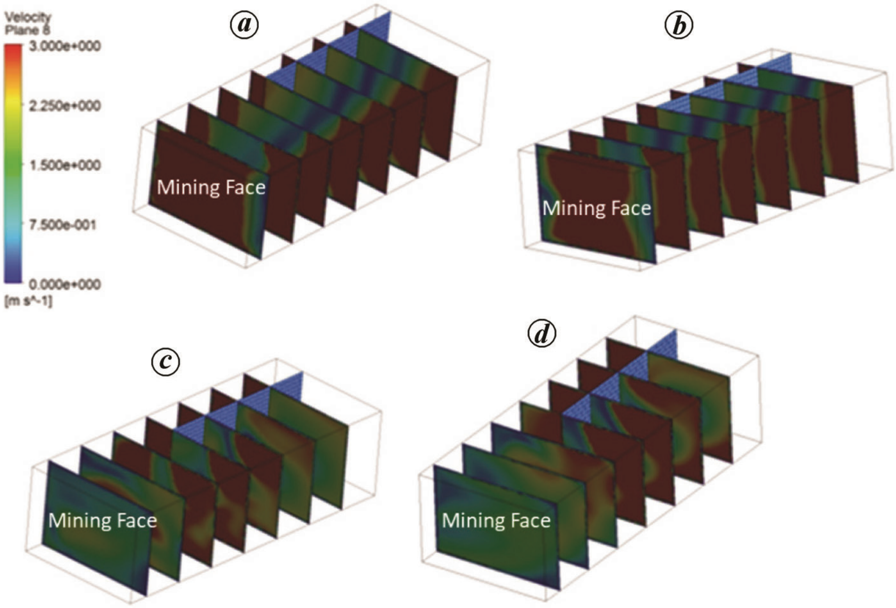


Figure 10. Contours of air velocity at 2 m intervals from the mining face at distinct line brattice distances from the side wall: ***a***, 0.75; ***b***, 1; ***c***, 1.5; ***d***, 2 m.

in the cross-sectional area of the brattice air inlet at a constant airflow. The increase in brattice line distance from the side wall not only decreases dust dispersion, but also poses operational difficulties for the large-dimension coal-cutting machines like the continuous miner. From this point of view, a shorter line brattice distance from the side wall is preferred in the development heading. Since the difference between the dust concentrations along the development heading in case of line brattice distances of 0.75 and 1 m was found to be marginal, one may choose any of these distances for proper dust dispersion in the development heading, depending on convenience.

Validation of simulation

The simulation results were validated with the actual field measurement data with respect to concentration of coal

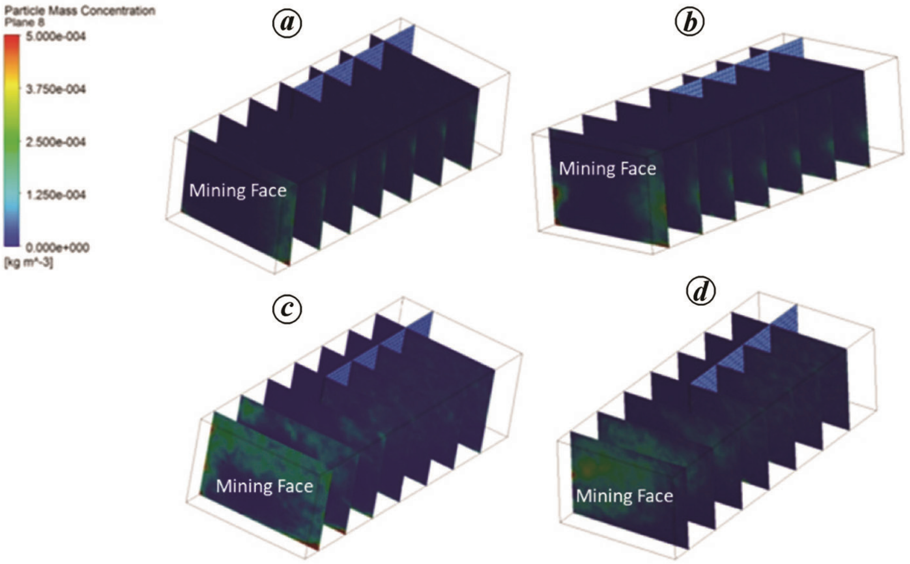


Figure 11. Contours of dust concentration at 2 m intervals from the mining face at distinct line brattice distances from the side wall: ***a***, 0.75; ***b***, 1; ***c***, 1.5; ***d***, 2 m.

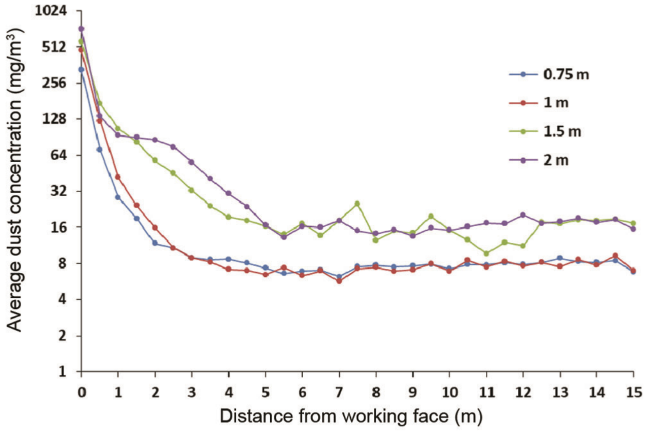


Figure 12. Variation of dust concentration along the development heading at different line brattice distances from the side wall.

dust in the development heading. It is to be mentioned here that these simulations were performed considering a number of auxiliary ventilation systems for studying dust dispersion behaviour in the underground coal mine development heading. The objective was to compare the efficacy of different auxiliary ventilation systems to identify the best system dispersing dust to a safe level. In actual mining conditions, it is difficult to change the ventilation systems for experimentation and carry out real-time dust measurement with each auxiliary ventilation system. Hence the forcing-type auxiliary ventilation used in the mine was considered for validation purpose. Moreover, no person other than the operator is allowed to enter the development mine heading during coal cutting by the continuous miner. Hence, special permission was taken from the mine management and dust concentration in the heading adopting forcing auxiliary ventilation was monitored at 6 m away from development heading face maintaining a safety distance. The concentration of coal dust at 6 m from the development face in the mine was recorded as 52.3 mg/m^3. From the simulation, the corresponding average dust concentration at the same location was 48.9 mg/m^3. An error of only 6.5% was observed between the field measurements and simulation results. This proves that the simulation results are in good agreement with the field measurements.

Conclusion

Choosing an appropriate auxiliary ventilation system for the development headings in underground coal mines is important for supplying adequate quantity of fresh air and maintaining the air pollutants at a safe level. This study numerically analysed the dispersion behaviour of coal dust in the underground development heading advanced by a continuous miner considering five different auxiliary ventilation systems, namely forcing, exhaust, overlapping, line brattice and a combination of line brattice and exhaust ventilation systems. It also examined the effect of variation of line brattice distance from the side wall on dust dispersion in the development heading. The efficacy of dust dispersion by different auxiliary ventilation systems was compared and the best system achieving maximum dust dispersion was identified. This study provides a better insight into the dust dispersion behaviour of different auxiliary ventilation systems in the development heading. The main conclusions drawn from this study are outlined below:

(1) Among the studied auxiliary ventilation systems, both line brattice and line brattice–exhaust combination

systems were found to be effective means of dust dispersion in the development headings.

(2) Considering other advantages, the line brattice system is preferred for dust dispersion over the line brattice–exhaust combination.

(3) A significant decrease in the concentration of dust in the development heading was achieved at line brattice distances of 0.75–1 m from the side wall at a particular airflow rate.

Conflict of interest: The authors declare that there is no conflict of interest.

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