Optimum Auxiliary Fan Location to Control Air Recirculation

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Abstract
This paper presents the optimum auxiliary fan(s) location to control air recirculation in dead-end workings where diesel-powered vehicles operate. Investigations were conducted with various secondary fan locations from the dead-end crosscut with varying the intake air quantities using a 30 m³/s capacity twin 75 kW auxiliary fan and 45 m³/s capacity twin 110 kW auxiliary fan to control air recirculation and DPM. The results showed that if the drive intake airflow rate matches the fan capacity, air recirculation will occur even when the fan is located 10 m away from the crosscut entry. Results also showed that if the intake drive air quantity was greater than or equal to 150% of fan capacity, no recirculation was observed when the twin 75 kW fan location was at least 5 m and the twin 110 kW fan location was at least 10 m away from the dead-end crosscut access.

Keywords Dead end · Recirculation · Auxiliary fan · Crosscut · DPF · DPM · CFD simulation

1 Introduction
Auxiliary fans are generally installed in fresh air raise (FAR) system or decline or level to supply fresh air to the workings in metal and nonmetal mines. The primary issue with the fan installation in decline or level is air recirculation. It mainly depends on the fan installation location from the level access and airflow in the intake drive. If a secondary fan is recirculating the air, there is a chance of increasing the concentrations of diesel vehicles exhaust fumes, heat, and dust. Prolonged exposure of miners to the high concentrations of diesel fumes may lead to health effects, including lung cancer [26, 31–33], Watts Jr, 1987, [23–25], USEPA, 2002, [36]. Diesel-powered vehicles are normally used in metal and nonmetal mine workings due to their flexibility, consistency, and durability than battery-powered or electric vehicles [5–7, 16]. The main concern with diesel vehicles in underground mine environments is their exhaust pollutants [17], including heat, pollutant gasses, and diesel particulate matter (DPM). DPM contains elemental carbon, organic carbon, and over 1800 organic compounds [5, 12, 14, 34, 35]. Different nations follow different regulations to control diesel exhaust fumes within the statutory limit. Different DPM control strategies have been investigated to control DPM in an underground mine environment, for example, the application of environmental cabs [28], passive particulate filters [27], and diesel particulate filters [3], by extending the ventilation ducts to the face [8]; monitoring engine conditions and maintaining the engine regularly [9], using positive pressure environmental cabs and water sprays [15], and using biodiesel [4, 11, 29], Bugarski1 and Shi, [1] and other alternative diesel [40].

This paper conducted investigations to control air recirculation and DPM concentration to optimize the auxiliary fan’s location and intake drive air quantity using field experiments and computational fluid dynamics (CFD). The present work describes simulations of airflow and DPM and controlling the air recirculation with different locations of the secondary fan for level access. The commercially available CFD package ANSYS Fluent was used. The CFD modelling studies
were carried out in a sequence of steps outlined in Sect. 2 below. In the previous investigations, the optimum auxiliary fan investigations have been conducted with a twin 75 kW fan [21, 22]. This paper conducted studies with twin 75 kW fan, twin 110 kW fan, and different fan pressures.

1.1 Field Experiment

Field experiments were conducted in one of the Australian metal mines. During the experiment, airflow in the main drive was regulated through a drop board regulator, and DPM concentration in the intake air was zero. The length, width, and height of experimental dead-end level access are 70 m, 6 m, and 5 m, respectively. During the experiment, a 306 kW LHD is working in a dead-end face, and a twin 75 kW fan with a 1.22 m diameter ventilation bag is ventilating the dead-end level access. The measured air velocity in the intake drive and the dead-end level access drive were 1.45 m/s and 1.0 m/s. The measured DPM concentration, dry bulb, and wet bulb temperatures in the dead-end face were 61.5 µg/m³, 25.8 °C, and 34.1 °C, respectively. An anemometer, real-time DPM monitor, and hygrometer were used to monitor air velocity, DPM concentration, and temperatures, respectively. Figure 1 shows the location of the fan, ventilation bag, LHD, and field monitored data.

2 CFD Modelling

2.1 Construction of Computational Domain

The computational domain consisted of a 100-m-long ventilation tunnel or drive and a 70-m-long dead-end level access drive/crosscut/ore drive. The width and height of the crosscut were 6 m and 5 m, respectively. The model also consists of a twin 75 kW fan with 50-m-long ventilation bag. A 3D CAD model of an LHD vehicle or bogger was imported into the dead-end crosscut. The computational domain geometry was generated as shown in Fig. 2. The model consisting of a fan, ventilation duct, and LHD was built to simulate auxiliary ventilation in underground dead-end level access.

2.2 Construction of Computational Mesh

Figure 3 shows the details of meshed LHD, ventilation bag with fan, intake air drive, and dead-end crosscut. A finer mesh with one million computational cells was selected to achieve the optimum results. The minimum edge length of the model was 0.03 m, cells’ minimum size was 5 × 10⁻³ m, and the size function was set as “proximity and curvature.” Program-controlled inflation with ten layers was specified for the solid surfaces in the mesh (channel walls, LHD surfaces, and ventilation duct surfaces) to simulate the boundary layer effects.

2.3 Setting Up Flow Conditions

The boundary conditions for the LHD exhaust are considered as exhaust air velocity of 24 m/s and exhaust fumes temperature of 345 K. The boundary conditions are considered for the intake airflow of 30 m³/s, 45 m³/s, 60 m³/s, 67.5 m³/s, and 90 m³/s, and the air temperature was 300 K. The twin 75 kW fan boundary conditions were considered as operating at an air quantity of 30 m³/s and twin 110 kW fan boundary conditions considered as operating at an air quantity of 45 m³/s. The discrete-phase modelling approach was used and considered...
DPM particles and mine air as different phases. The chemical reaction of DPM particles is not considered. The Boussinesq approximation with buoyancy correction was invoked to simulate the buoyancy effects \cite{18–20, 37}. The standard Reynolds stress model was used to simulate the turbulence, and the flow was considered a steady state.

3 Results and Discussions

3.1 Results of Field Experiment and Model Validation

The CFD model was validated against field measurements. Figure 4 shows the details of the intake drive, fan, ventilation bag, and dead-end crosscut. The average air velocity of the intake and return air side of the drive and crosscut was measured with a vane anemometer using the traverse method. Figure 4a and b shows the field data and CFD simulated results. Some differences between the simulated and measured field results can be observed due to the unevenness in the drive or crosscut wall surfaces that was not considered while modelling. Overall, the difference varies from $-3$ to $+3\%$.

3.2 Effect of Air Recirculation on Twin 75 kW Auxiliary Fan Location

3.2.1 The Airflow in the Intake Drive Is the Same as Fan Capacity, 150% and 200% More Than Fan Capacity

Simulations were conducted with 30 m$^3$/s airflow rate (same as the fan), 45 m$^3$/s (150% of the fan capacity), and 60 m$^3$/s
(200% of the fan capacity) in the main intake gallery and with different fan locations of 0 m, 1 m, 2 m, 3 m, 4 m, 5 m, and 10 m from the crosscut. Location of a fan means the location of the fan delivery point in the modelling, the considered length of a twin 55 kW fan is 5 m, and the length of a twin 110 kW fan is 7 m. Figure 5 shows the results of

![Image](image-url)
simulation studies when the intake air quantity is 60 m$^3$/s (200% of the fan capacity). The results showed that air recirculation occurred from 0 to 4 m from the crosscut entry fan. No recirculation is observed for 5 m and 10 m from the crosscut fan locations.

Table 1 and Fig. 6 show the recirculation air percentage with respect to the secondary fan location from the crosscut entry in the intake air drive with different air quantities in the intake air drive. From the table and figure, it can be observed that when the fan was in line with the crosscut (0 m), most of the secondary fan air was recirculating. The amount of recirculation air decreased with increased fan location from the crosscut. If the intake air quantity is the same as fan capacity, recirculation occurs even when the fan location is 10 m from the crosscut. If an intake air flow rate is of 45 m$^3$/s (150% of the fan capacity), maximum recirculation was observed when the fan was in line with the crosscut (0 m). Recirculation was gradually reduced from 1 to 4 m of fan location from the crosscut. At 5 m and 10 m distance

### Table 1 Percentage of air recirculation with respect to fan location from the crosscut entry

| Air quantity in intake drive | Percentage of recirculation air in a secondary fan |
|-----------------------------|-----------------------------------------------|
|                             | Location of a secondary fan from the crosscut entry |
|                             | 0 m  | 1 m  | 2 m  | 3 m  | 4 m  | 5 m  | 10 m |
| 30 m$^3$/s                  | 54%  | 46%  | 41%  | 37%  | 31%  | 24%  | 15%  |
| 45 m$^3$/s                  | 36%  | 29%  | 22%  | 18%  | 10%  | 4%   | 0    |
| 60 m$^3$/s                  | 27%  | 20%  | 16%  | 9%   | 3%   | 0    | 0    |

![Air recirculation percentage w.r.t. intake air quantity and secondary fan location](image)

**Fig. 6** Air recirculation percentage w.r.t intake air quantity and secondary fan location

![DPM concentration after 30 min, 2 h, and 6 h at 70-m dead-end crosscuts](image)

**Fig. 7** DPM concentration after 30 min, 2 h, and 6 h at 70-m dead-end crosscuts
from the crosscut, no air recirculation was observed. If an intake air quantity is of 60 m³/s (twice the fan capacity), air recirculation occurred from 0 to 4 m of the fan location from the crosscut entry. No recirculation is seen for fan locations of 5 m and 10 m from the crosscut.

### 3.3 Results of DPM Distribution in 70-m-Long Unventilated Dead-End Crosscut

To investigate the characteristics of DPM accumulation and dispersion in dead-end zones, simulation studies were carried out for the 70-m-long dead-end crosscut with no secondary ventilation. For this simulation, initially, the crosscuts were filled with 820 µg/m³ of DPM. The effect on the concentration of DPM in the dead-end crosscut was monitored with respect to time. Figure 7 shows the dispersion of DPM concentration in a 70-m dead-end crosscut with respect to time. The figure shows that after 30 min, 2 h, and 6 h, the spot concentrations of DPM were 820 µg/m³, 505 µg/m³, and 100 µg/m³, respectively.

### 3.4 DPM Concentration Variations with Recirculation

Figure 8a shows the DPM concentration generated by LHD in a dead-end crosscut. This heading is ventilated by a twin 75 kW fan located in the intake drive and is in line with the crosscut. The average DPM concentration at 5 m from the face is 70 µg/m³. Similarly, Fig. 8b shows the DPM concentration generated by LHD in a dead-end crosscut. This heading is ventilated by a twin 75 kW fan located in the intake drive and is 10 m from the crosscut. The average DPM concentration at 5 m from the face is 61.5 µg/m³. In both cases, intake drive quantity is 60 m³/s, and fan quantity is 30 m³/s. The results show that if the fan is in line with the crosscut DPM concentration, it is 13.8% more than the...
fan location 10 m from the crosscut due to air recirculation. When the 70 m drive was filled with a DPM concentration of 820 µg/m³ and no recirculation at the secondary fan, it took 127 s for the auxiliary fan to clear the DPM particles from the drive.

### 3.5 Effect of Air Recirculation on Twin 110 kW Auxiliary Fan Location

Table 2 and Fig. 9 show the recirculation air percentage with respect to the twin 110 kW fan location from the crosscut entry in the intake air drive with different air quantities in the intake air drive. From the table and figure, it can be observed that when the fan was 2 m from the crosscut, most of the secondary fan air was recirculating. The amount of recirculation air decreased with increased fan location from the crosscut. If the intake air quantity is the same as fan capacity, recirculation occurs even when the fan location is 10 m from the crosscut. If an intake air flow rate is of 67.5 m³/s (150% of the fan capacity), maximum recirculation was observed when the fan was 2 m from the crosscut. Recirculation was gradually reduced from 2 to 8 m of fan location from the crosscut. No air recirculation was seen at a 10 m distance from the crosscut. If an intake air quantity is of 90 m³/s (twice the fan capacity), air recirculation occurs from 2 to 6 m of the fan location from the crosscut entry. No recirculation is seen for fan locations of 8 m and 10 m from the crosscut.

### 3.6 Effect of Air Recirculation on Auxiliary Fan Pressure and Location

The airflow of the auxiliary fan is influenced by its pressure [10, 13, 30]. Modelling studies have been conducted with different fan pressures and air quantities. For this modelling, the considered pressure and quantity of a twin 132 kW fan is 1200 Pa and 50 m³/s, a twin 110 kW fan is 1000 Pa and 45 m³/s, a twin 90 kW fan is 800 Pa and 40 m³/s, a twin 75 kW fan is 600 Pa and 30 m³/s, and twin 55 kW fan is 400 Pa and 27 m³/s.

Intake airflow of the drive is considered as 45 m³/s. Table 3 and Fig. 10 show the recirculation air percentage with respect to different fan pressures and location from the crosscut entry and in the intake air drive air quantity of 45 m³/s. From the table and figure, it can be observed that when the fan was 2 m from the crosscut, most of the secondary fans are recirculating. The amount of recirculation air increase with increased fan pressures.

### 4 Conclusions

This paper describes the best location of an auxiliary fan for the minimum amount of air needed in the intake drive to control air recirculation in dead-end crosscuts where diesel-powered vehicles operate. Results concluded that a 70-m-long unventilated dead-end crosscut took 6 h to reduce the DPM from 820 to 100 µg/m³. Field monitoring and CFD simulation studies were carried out with intake drive air quantities of 1.0, 1.5, and 2.0 times of the airflow from twin 55 kW and twin 110 kW auxiliary fans located at 1 to 10 m away from the crosscut entrance. These studies demonstrated that the air was always recirculated if the quantity of intake

| Secondary fan pressure | 2 m | 4 m | 6 m | 8 m | 10 m |
|------------------------|-----|-----|-----|-----|------|
| 1200 Pa                | 54% | 45% | 40% | 32% | 27%  |
| 1000 Pa                | 43% | 35% | 31% | 23% | 18%  |
| 800 Pa                 | 32% | 23% | 20% | 13% | 9%   |
| 600 Pa                 | 22% | 13% | 10% | 3%  | 0%   |
| 400 Pa                 | 10% | 4%  | 0%  | 0%  | 0%   |
drive air was the same as the fan capacity. However, the amount of recirculated air decreased as the distance between the fan and the crosscut increased. Studies also showed that if the intake drive quantity was higher than or equal to 150% of the fan capacity, there would be no recirculation when the twin 75 kW fan was at least 5 m and the twin 110 kW fan was at least 10 m away from the crosscut entrance.

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**Declarations**

**Conflict of Interest** The authors declare no competing interests.

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