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Abstract

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Keywords

dust, respirable, modelling, face, dynamics, longwall, fluid, computational, behaviour, gas

Disciplines

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Computational Fluid Dynamics Modelling of Respirable Dust and Gas Behaviour on a Longwall Face

T Ren[1] and Z Wang[2]

ABSTRACT

Longwall mining is the dominant form of underground coal mining methods in Australia. As production increases there is also a need for increased face ventilation rate for gas dilution and dust mitigation. The behaviour of gas emission and respirable dust in a longwall face is a complex process because of the nature of longwall operations. The generation, dispersion and transport of airborne dust and gas are governed mainly by the spatial velocity and the movement pattern of the ventilation air. To understand the gas and dust behaviour in a complex longwall mining environment and to evaluate the effectiveness of various dust control techniques, numerical modelling has become a necessity to supplement laboratory experiments and field studies. Three-dimensional (3D) computational fluid dynamics (CFD) model was developed based on a longwall face extracting a medium seam (3.2 m) to investigate the aerodynamics of methane gas emitting from drum cutting actions, and respirable dust from different sources. The model was developed to incorporate key features on the longwall, including the shearer, armoured face conveyor (AFC), chocks, outbye facilities and dust control devices. The base CFD model was calibrated using field ventilation survey data and used to study the behaviour of longwall gas and dust dispersion patterns that are vital to the safety and productivity of the longwall face.

INTRODUCTION

Longwall mining is the primary form of underground mining methods in Australia, with the increase of coal production, there is also an increase in dust and gas liberation along the longwall face. The complexity of underground mining conditions makes it difficult to determine the spatial flow behaviour of gas and dust particles by conventional approaches. For instance, the measured methane concentration by the real-time gas monitors installed on gob-side tailgate-end of the shearer is 40 - 50 per cent lower than that measured at the face side (Kissell, 2006). A better understanding of ventilation flow patterns on a longwall face is needed for face ventilation management to ensure the adequate dilution of gas emissions and hazardous dust particles from the coal cutting process.

The computational fluid dynamics (CFD) modelling technique has been widely used in solving flow-related engineering problems, and the ventilation in mining is no exception. Using a simplified three-dimensional longwall face model, Srinivasa managed to predict the dust concentration around the shearer using the Lagrangian method, and good agreement with experimental data was reported (Srinivasa, 1993). Sullivan and Heerden (1993), Moloney, Lowndes and Hargreaves (1999), Moloney and Lowndes (1999), Hargreaves and Lowndes (2007), Toraño *et al* (2009), conducted CFD studies on airflow patterns within the development headings under various ventilation scenarios by solving the standard k-ε model. (The standard k-ε model is a model based on model transport equations for the turbulence kinetic energy (k) and its dissipation rate (ε). Please refer to ANSYS (2010) for more information about the standard k-ε model). Ren and Srinivasa (2007), Ren and Balusu (2008, 2010) developed a more detailed longwall model to predict both the airflow and dust flow behaviour at typical longwall faces using the Lagrangian particle tracking method. Toraño *et al* (2011) investigated the effect of auxiliary ventilation on the dust behaviour in headings driven with roadheader. By solving the species transport equations, Ren *et al* (2012a) predicted the gas distribution in a longwall goaf with Y type ventilation, and successfully mapped the spatial distribution of spontaneous combustion prone zones where effective inertisation strategies were proposed and evaluated. More recently, Xu *et al* (2013) conducted CFD studies to investigate the impact of ventilation controls on airflow inside a mine, and simulated the use of tracer gas for ventilation damage detection. To understand the dust and gas behaviour in a complex longwall mining environment and evaluate the effectiveness of various gas and dust control techniques, CFD modelling has become a useful tool to supplement laboratory experiments and field studies.

In this paper, a 3D CFD model was developed based upon a longwall face in Australia. The scenario presented here is when the shearer extracts coal from maingate (MG) to tailgate (TG). The base CFD model was calibrated using field

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ventilation survey data, before it was used for parametric studies of face ventilation pattern and gas accumulation around the shearer, as well as dust dispersion and mitigation options using venturi sprays.

THE LONGWALL COMPUTATIONAL FLUID DYNAMICS MODEL

Based on field data collected from an Australian longwall face, a 3D CFD model incorporating the key features of the longwall face, including 103 chocks, the shearer, armoured face conveyor (AFC), beam stage loader (BSL) and belt conveyor, were constructed. A commercial CFD code ANSYS-Fluent is used as the modelling tool (ANSYS, 2010). Figure 1 shows the geometry layout of the CFD model representing a longwall operating scenario when the shearer was cutting from the MG to TG and the MG drum is 10 m from the MG rib. The model also incorporates two rows of 'water sprays' mounted under the chock canopy and the coal transfer point from face to the BSL to investigate the effect of various dust control options of using venturi sprays. The longwall face has a physical domain of 156.5 m (face length) × 50 m (MG length) × 3.2 m (face cutting height), and the last cut through at 45 m outbye the face. The model was meshed into 1.8 million control volumes using the unstructured tetrahedron approach to accommodate its complex geometry. Figure 2 shows the computational mesh adopted for the CFD model.

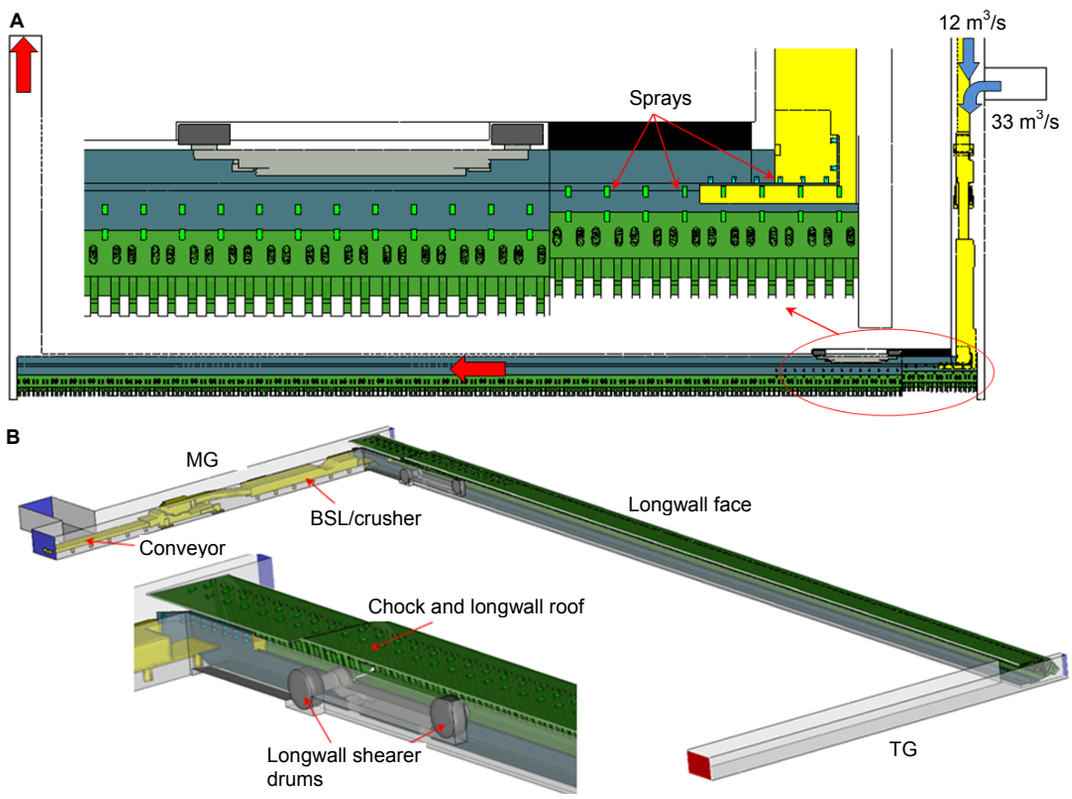

FIG 1 - Layout of the longwall computational fluid dynamics (CFD) model (Ren *et al*, 2012b). (A) Plan view of the longwall CFD model; (B) 3D view of the longwall CFD model.

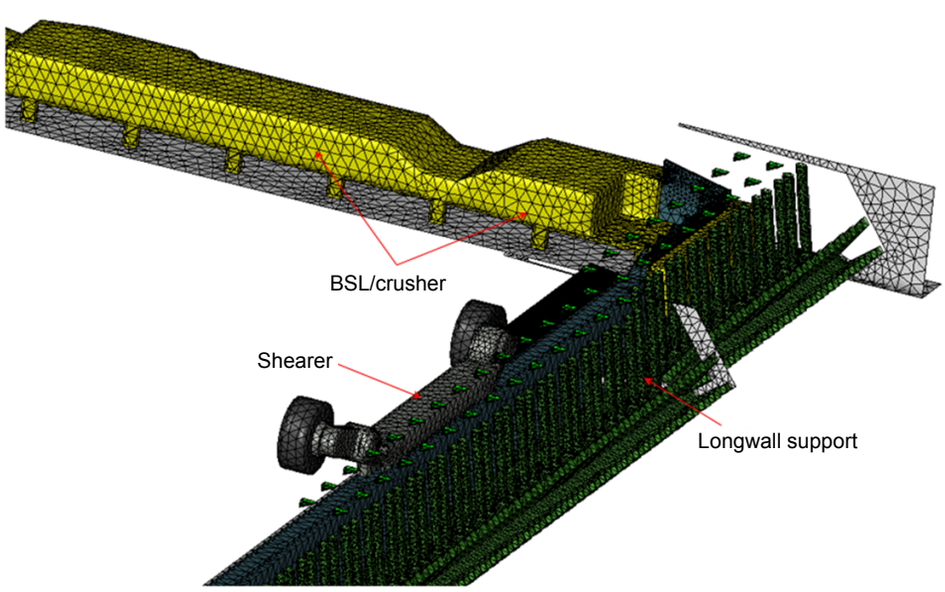

FIG 2 - Computational grid for the computational fluid dynamics (CFD) model (Ren *et al*, 2012b).

The boundary conditions were categorised into different types during the meshing process so that different boundary conditions can be conveniently applied in the CFD modelling process. As shown in Figure 1, boundary conditions involved in the model were typically velocity inlet for the MG and cut through, pressure outlet for the TG, and standard wall for all other boundaries except the shearer drums, which were treated as moving wall with a rotational speed of 35 rev/min to investigate its local influence on airflow patterns in the vicinity of shearer. The longwall face was ventilated with 45 m^3/s air, of which 33 m^3/s flowed from the last cut through (velocity inlet). In this study, it is assumed that the flow medium (air) is incompressible and the temperature field is constant, thus the inlet ventilation velocity can be calculated for both MG and the last cut through.

BASE MODEL VALIDATION

As an important step in numerical simulation, base model results must be validated against field data or experimental measurements before it can be used for parametric studies. In this study, the distribution of airflow velocity at five cross-sections along the MG and face (mostly around the shearer) was measured during a field ventilation survey and subsequently used to validate the base model. It is noted that the velocity was measured using the hand-held anemometers rather than the vane anemometers, thus the velocity measurement can be obtained at selected positions of a specific cross-section. Figure 3 shows a comparison of model predicted results and field measured velocity at the five cross-sections.

It can be seen from Figure 3a that, due to the space constraints by BSL/crusher and associated equipment, airflow travels much faster along the walkway in the MG before entering

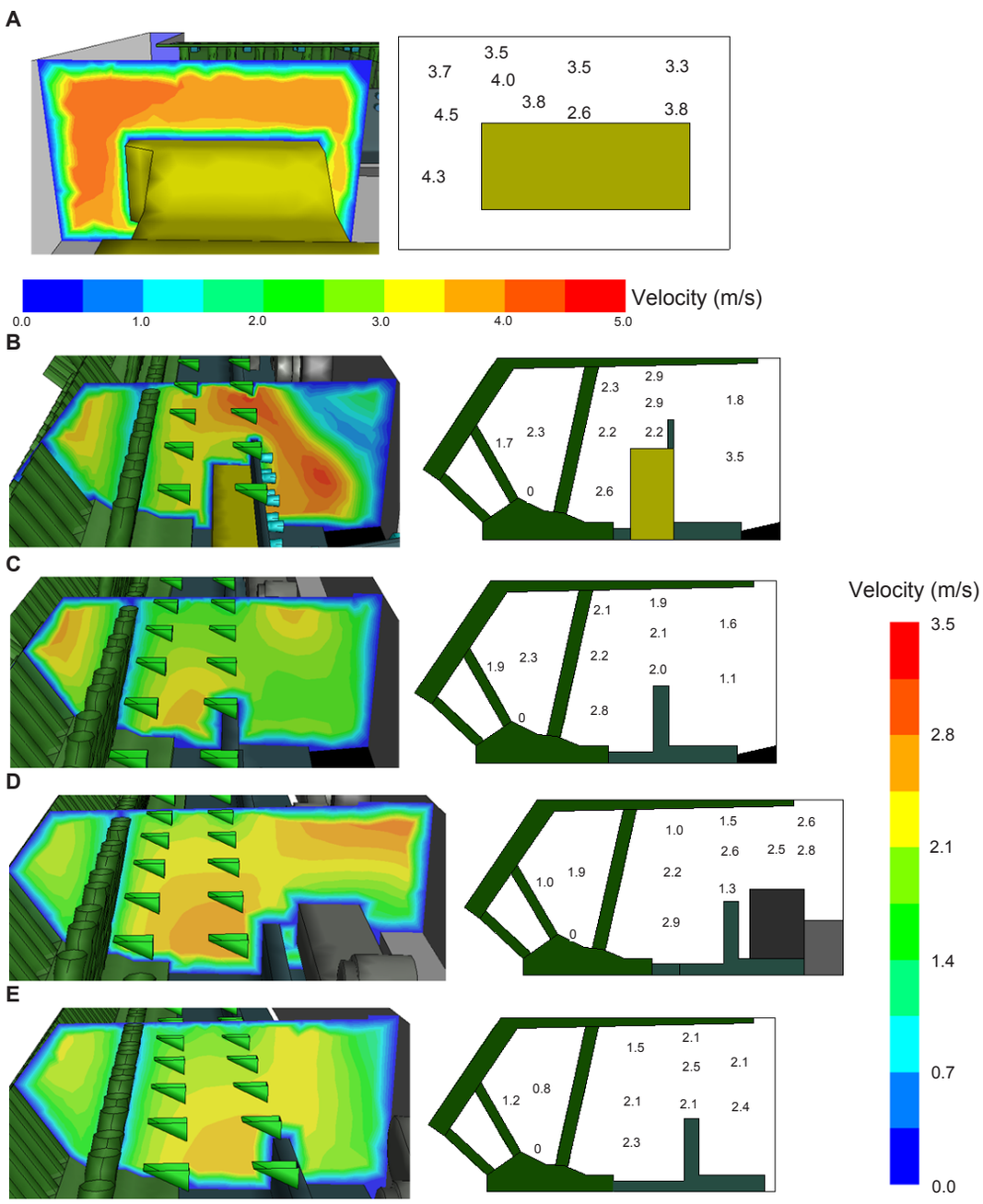

FIG 3 - Validation of computational fluid dynamics (CFD) model – predicted airflow velocity versus field ventilation survey data. (A) Velocity distribution at 5 m outbye the face (in maingate); (B) velocity distribution at 1 m from main gate; (C) velocity distribution at 2 m before the maingate drum; (D) velocity distribution in the middle of the shearer; (E) velocity distribution at 2 m behind the tailgate drum.

the face, which may lead to serious air leakage into the goaf if no goaf curtain is used in the gap between chock and MG rib. In this model the leakage through the gaps in the chocks is not considered. As the ventilation enters the longwall face with relatively larger cross areas, it then travels at a slightly lower velocity, with the maximum value around 3.5 m/s. It is also observed that airflow velocities are not evenly distributed across these sections and high velocity area tends to appear in the walkway and higher part above AFC except the intersection between MG and face where high velocity areas are directly above AFC and longwall control and communication panel. In general, the predicted air profiles predicted by the CFD model are in reasonable agreement with field ventilation survey data and thus the model can be used to investigate ventilation airflow pattern, gas and dust dispersion behaviour on the longwall face.

LONGWALL FACE VENTILATION PATTERNS

Figures 4 and 5, respectively, show the airflow velocity contours and vectors at different elevations on the longwall face. As the fresh air approaches the face, the velocity in the walkway area is much higher in the MG due to the obstruction of equipment in the roadway; the maximum velocity can reach 4.5 m/s or above. It can also be observed that the ventilation velocity is also higher in the MG corner where the airflow changes direction from MG onto the face, resulting in the occurrence of flow separation and air leakage into the goaf. As the ventilation travels down the face, airflow velocity changes significantly around the shearer across the face due to the change of cross-sections and obstruction of longwall equipment, with higher velocity area at the walkway side approximately parallel to the MG drum and immediately behind the MG shearer arm. When the airflow gradually passes by the shearer body, airflow velocity increases in the walkway next to the shearer arms; this could be attributed to the fact that when the shearer is cutting from MG to TG, the advance of chock immediately behind the shearer and the appearance of shearer body reduce the effective cross-section for ventilation. Modelling results show that the impact of rotating drums on the airflow is found to be minor at the lower section but significantly increased as approaching the top of the drum. Figure 5 illustrates the velocity vectors on the two elevations corresponding to Figure 4, indicating both the individual flow direction and magnitude in the vicinity of shearer. As can be seen in Figure 5, the airflow is forced to flow backwards to the walkway when the ventilation impacts on the shearer body, thus increasing the flow velocity in the walkway. The slow movement of airflow between the longwall chocks due to the obstruction of chock legs can be clearly observed in these modelling results. Low velocity areas can also be observed near the shearer body behind ranging arms and close to the wall.

GAS DISPERSION FROM COAL CUTTING BY LONGWALL SHEARER

As the shearer cuts coal from the face, gas is emitted instantly from the newly exposed coals on the wall and those on the AFC. The fast desorption of gas from the cutting ribs may result in gas accumulation around the shearer drums depending on the gas content and ventilation patterns, and potentially leading to longwall power trips, in the worst case, gas explosions. To investigate the liberated gas flow characteristics, five small zones (as shown in Figure 6) with a total volume of 3.74 m^3 (Figure 6 shows the projected areas of the zones on the rib, and the actual gas emission zones are assumed to have a thickness of 0.2 m), close to the fresh ribs, were defined as gas source using the user defined function (UDF), which can be hooked to the main CFD solvers. It was assumed that the gas emission rate per unit volume was constant. The gas released in the model was pure methane at 30 L/s (this quantity is assumed according to the authors' experience, the actual gas emission due to shearer cutting is

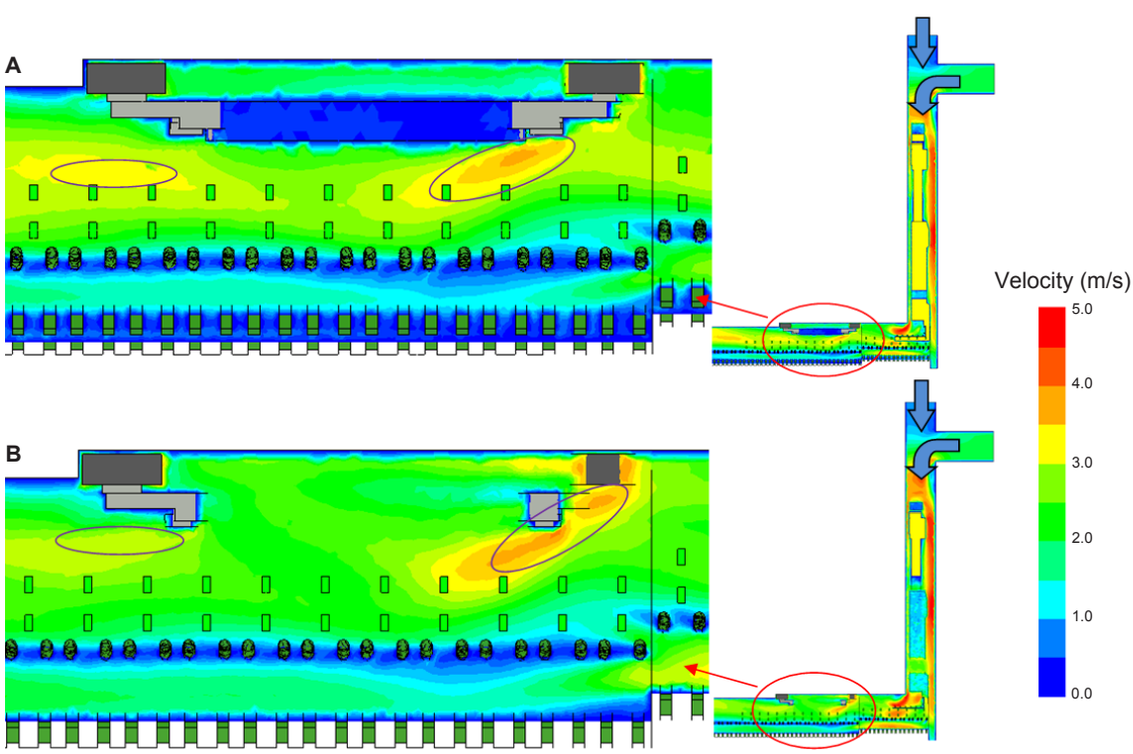

FIG 4 - Airflow velocity contours in maingate and near the shearer. (A) Airflow velocity contours at 1.5 m above floor; (B) airflow velocity contours at 2 m above floor.

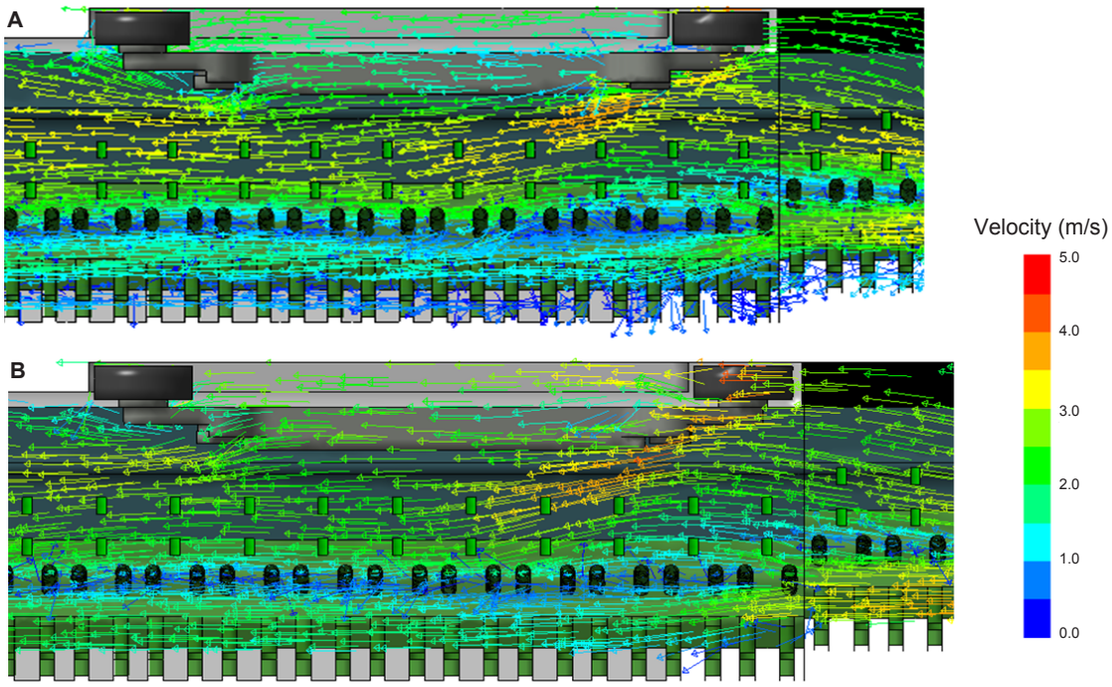

FIG 5 - Airflow velocity vectors around the longwall shearer. (a) Airflow velocity vectors at 1.5 m above floor; (B) airflow velocity vectors at 2 m above floor.

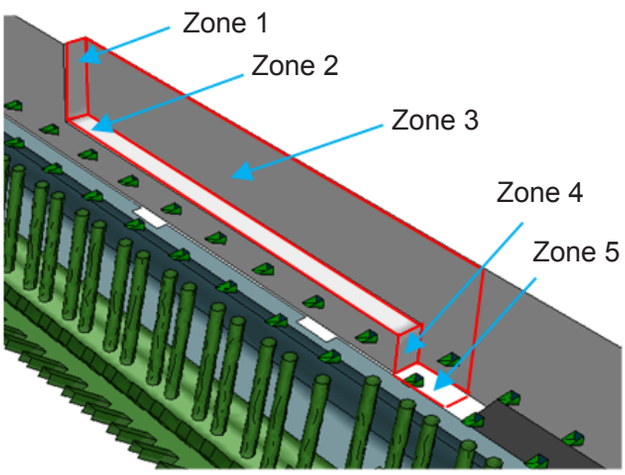

FIG 6 - Longwall face gas emission zones from shearer cutting.

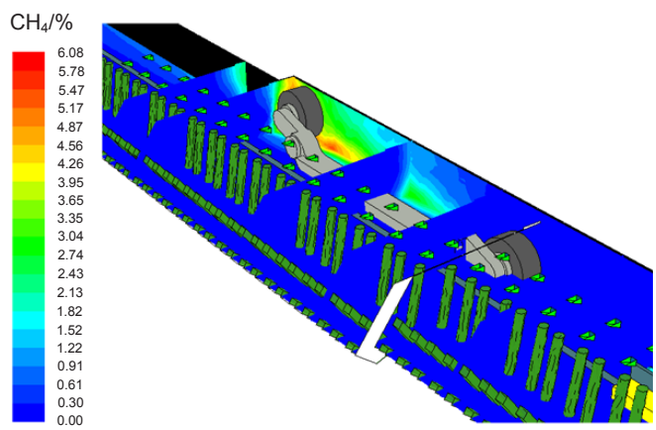

FIG 7 - Gas distribution in the vicinity of shearer at selected cross-sections – 3D view.

a complex process, and desorption tests can be conducted to determine its value; however, this is beyond the extent of this study). The water spray mounted on the cutting drums and shearer was not modelled in this study.

Figures 7 and 8 respectively illustrate the gas concentration contour around the shearer at selected cross-sections in 3D and plan view. It can be seen that when the shearer is cutting from MG to TG, the maximum gas concentration can reach as high as 6.08 per cent[3] in the 'dead' areas close to the face and around the cutting drum. It is also observed that gas liberated around the MG drum is diluted instantly by face ventilation; however, gas is likely to accumulate around the TG drum, particularly at the lower section where the gas concentration is the highest. The generation of this kind of gas accumulation characteristics can be attributed to two factors. First, as the cutting height is 3.2 m in the model and the diameter of drum is 2 m with a web depth of 0.6 m, so the vertical and horizontal fresh ribs (zone 3 and zone 2 in Figure 6, respectively) become the major gas contributor. Second, as the shearer is cutting form MG to TG, the TG drum constitutes an impermeable curtain hindering the flow of ventilation to dilute the gas emitted from the newly extracted coal face, which provides a suitable condition for gas to accumulate around the TG drum. This phenomenon is better illustrated in Figure 9 where a 3D view of velocity vectors is illustrated. The modelling results also show that both ranging arms and the shearer body are staying clear of gas accumulation due to sufficient ventilation dilution; therefore gas monitors positioned on shearer body or ranging arms may fail to detect a potentially explosive atmosphere that could occur just around the cutting drum.

Figure 10 shows the gas concentration iso-surface at two per cent when the longwall is ventilated with different ventilation rates. Modelling results show that a zone of methane concentration greater than two per cent (below the iso-surface) can exist in the vicinity of the shearer, and for a longwall face with 30 L/s gas emission from coal cutting, the ventilation rate

3. The use of two decimals here does not mean to show the degree of precision; more decimals are available according to the users' preference. To justify the accuracy of the model results, filed measurements or laboratory tests are necessary, but they are currently not available in the paper.

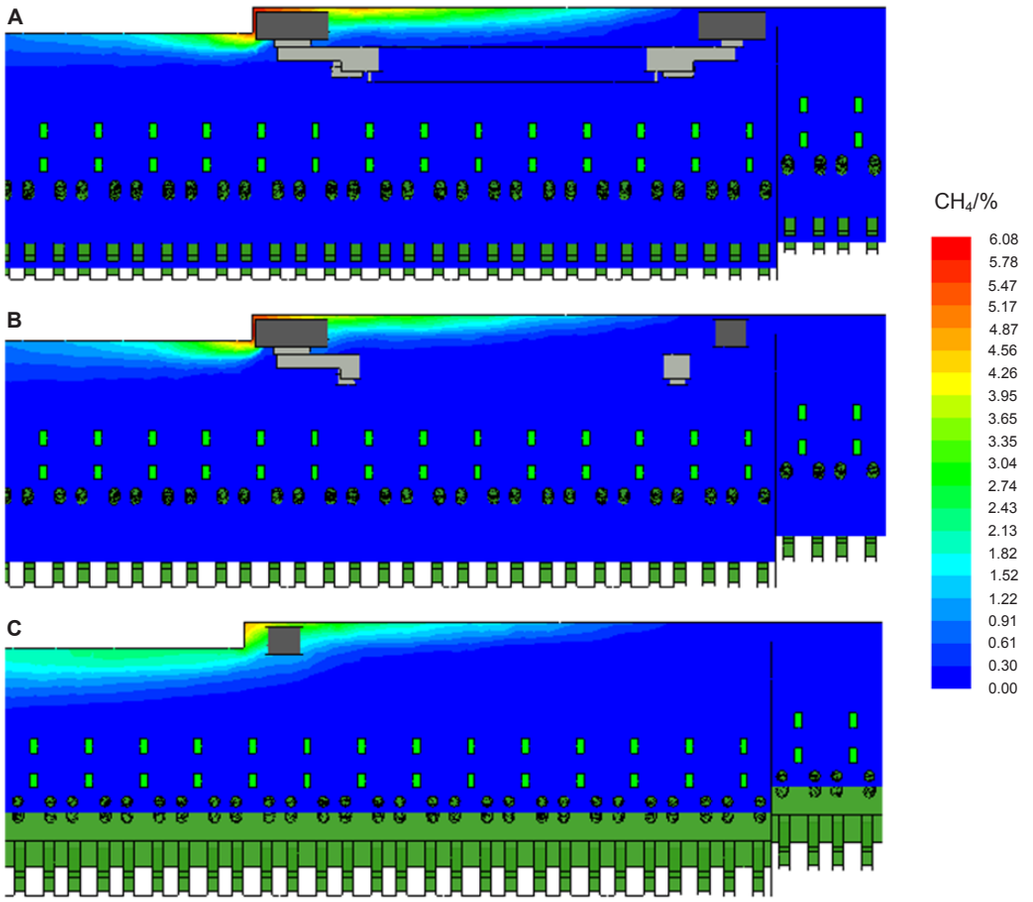

FIG 8 - Gas distribution in the vicinity of shearer at selected cross-sections – plan view. (A) 1.5 m above floor; (B) 2 m above floor; (C) 3 m above floor.

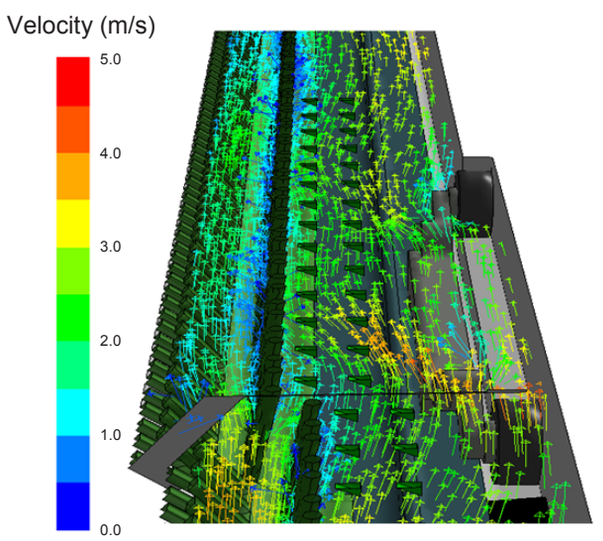

FIG 9 - Three-dimensional view of velocity vectors in the vicinity of shearer (2 m above floor).

at 45 m^3/s appears to be insufficient to dilute such gas emission below a safe level. Modelling results clearly show that methane gas sensors located beyond the iso-surface will not be able to detect such a dangerous condition around the cutting drum.

DUST DISPERSION PATTERNS IN THE LONGWALL FACE

Respirable dust particles have long been known to be a serious health hazard to workers in coal mining. These dust particles can be generated from several sources on the longwall, primarily including shear cutting, chock movements, stage loader/crusher and intake contaminations. To understand the dust dispersion characteristics in the longwall face, groups of respirable dust were released as coal-hv (material) with particle sizes between 1 - 10 µm from potential dust sources, in this study, including MG belt, AFC-BSL transfer point and longwall chocks. The particle size distribution at each of the releasing locations was assumed to follow Rosin-Rammler distribution function. The dispersion of particles due to turbulence in the continuous phase flow phase (air) was tracked using the discrete random walk (DRW) model, which includes the effect of instantaneous turbulent velocity fluctuations on the particle trajectories through the use of stochastic methods. The fluctuating velocities are assumed to follow a Gaussian probability distribution in the DRW model; therefore, the fluctuating components can be defined as:

$$u' = \zeta\sqrt{\overline{u'^2}} = \sqrt{2k/3} \qquad (1)$$

where:

u′ is the fluctuating velocity components
ζ is a normally distributed random number
k is the turbulent kinetic energy (ANSYS, 2010)

By substituting the velocity into the particle momentum equation, each particle trajectory could then be determined considering the interaction between particles and the modelled flow field at each instance in time (ANSYS, 2010).

Figure 11 shows the tracking of these particles released from MG outbye, AFC-BSL transfer point, and the gaps during movement of chocks in the case of shearer cutting from MG

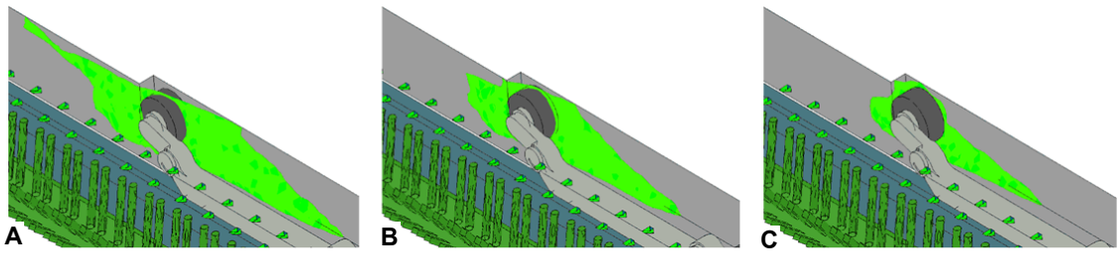

FIG 10 - Gas concentration iso-surface at two per cent methane with face gas emission of 30 L/s. (A) Face ventilation at 45 m^3/s; (B) face ventilation 55 m^3/s; (C) face ventilation 70 m^3/s.

to TG. Modelling results show that dust generated from MG account for a large proportion of dust exposure levels for personnel around the longwall control and communication panel, and this impact can extend to the shearer operators further down the face, while the coal transfer point does not make as much dust as MG belt to the walkway. It is also observed that the generation of dust particles due to chock movements behind the shearer is undoubtedly a major contributor to shearer operators' high respirable dust exposure levels. CFD modelling results show that much of the respirable dust particles generated from chock movements near the MG and outbye will end up on the longwall following the ventilation, contributing significantly to dust exposure on longwalls, if not controlled by effective dust mitigation methods. To avoid exposure from the majority of dust produced during chocks advancement, the uni-directional cutting sequence has been adopted in many underground coal mines (Aziz, 2009), which only allows shearer cutting coal from TG to MG, thus the shearer operators are kept upwind from the moving chocks.

IMPACT OF VENTURI SPRAYS ON RESPIRABLE DUST FLOW BEHAVIOUR

Operational experiences have demonstrated that it is unlikely to achieve total dust capture for any longwall dust control system due to the large cross-sectional area and high airflow on the face. A water mist-based venturi system has been designed as a stand-alone module that can be easily attached to the chocks' canopy and adjusted with the right spray angle to achieve the droplet size and velocity needed for dust suppression and diversion. In addition to capturing a proportion of the dust particles, the venturi unit can be positioned to divert dust particles away from the operators' walkway area.

Based on the understanding of the dust flow behaviour from the CFD modelling results, two rows of water-mist sprays were mounted under the chock canopy and the AFC/BSL plate respectively to investigate the corresponding dust suppression effects (refer to Figure 1). The operation of these sprays were modelled as 'air spray' as much of the spray would be of compressed air with a small portion of fogged water droplets, and the sprays can be operated individually or in groups (Ren, Cooper and Srinivasa, 2011).

Sprays mounted under the first six chocks were turned on to reduce the dust exposure levels around the communication panel, and various operating options were applied to these sprays to obtain a good dust suppression effect. Figure 12 indicates how these sprays can affect the dust dispersion pattern by changing the regional airflow patterns at the corner. It can be seen that a better dust suppression result can be achieved when this group of sprays are oriented at 30° down and 20° along the longwall face (towards the TG). As the spray is built as a stand-alone module with a magnetic base, it can be easily attached to the chocks' canopy and adjusted with the right spray angle to achieve a good dust suppression effect. Please refer to Ren *et al* (2012b) for more information about the design of the spray system.

CONCLUSIONS

The development of the computational modelling technique makes it possible to set up more realistic and complex simulations of mine ventilation and safety problems in underground coal mines. In this study, a 3D longwall CFD model incorporating the key structures of longwall face has been developed based on an Australian longwall face. The base CFD model was validated using field ventilation survey data, and used to investigate both the respirable dust flow behaviour and methane gas accumulation mechanism on a typical longwall face. It can be concluded from the CFD results that:

- airflow velocity is unevenly distributed across the longwall face
- due to the obstruction of equipment in the MG and the face, the effective ventilation section is reduced, airflow velocity is increased in the walkway next to the shearer
- a zone of methane concentration greater than two per cent can exist in the vicinity of the shearer, and gas sensors located on the ranging arms or shearer body may fail to detect such a dangerous condition around the cutting drum
- dust generated from MG belt road and chocks movement immediately behind the shearer is the main contributor to operators' dust exposure level
- effective dust suppression can be achieved with the application of water sprays oriented at certain directions, however, the optimal operating conditions for sprays mounted at different locations can vary.

It is worthwhile noting that the observations from this study are applicable and limited to the particular scenario modelled. The results may vary for other scenarios encountered in the longwall mining operation in terms of different coal seam properties, panel layout, ventilation system and shearer position. These scenarios need to be involved to better understand the dust and gas related issues on longwall faces. Additionally, an active goaf immediately behind the chocks can also be added to the longwall face model to further investigate the air exchange between face and goaf and the gas flow characteristics in the goaf.

ACKNOWLEDGEMENTS

Thanks are due to the mine staff of Metropolitan Colliery for providing the data and access to the underground for conducting field ventilation survey and observations. Scholarship from China Scholarship Council and the University of Wollongong for the second author are acknowledged.

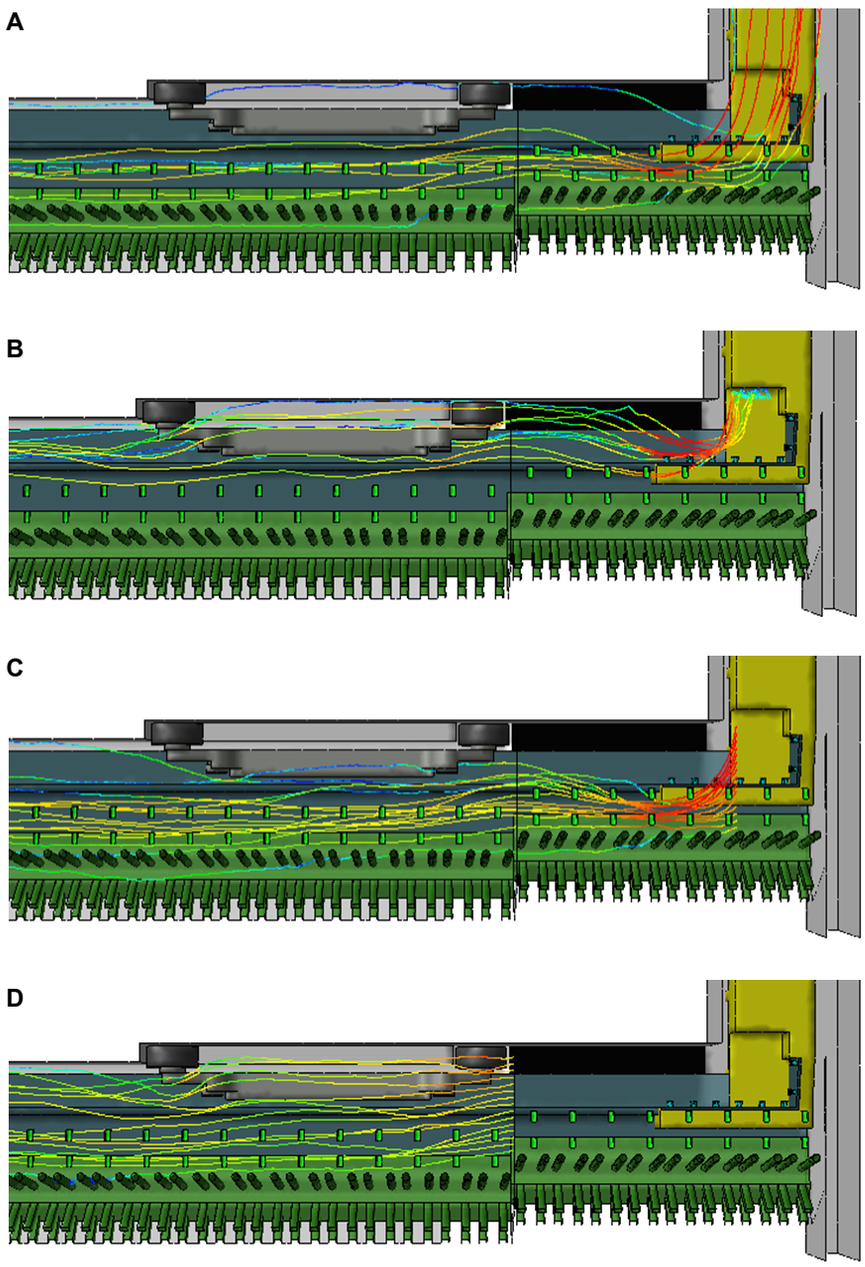

FIG 11 - Dispersion of respirable dust particles released from maingate (MG), beam stage loader and longwall chocks (Ren *et al*, 2012b). (A) Dust particles from MG outbye; (B) dust particles from coal transfer point; (C) dust particles from MG chocks; (D) dust particles from chocks behind shearer.

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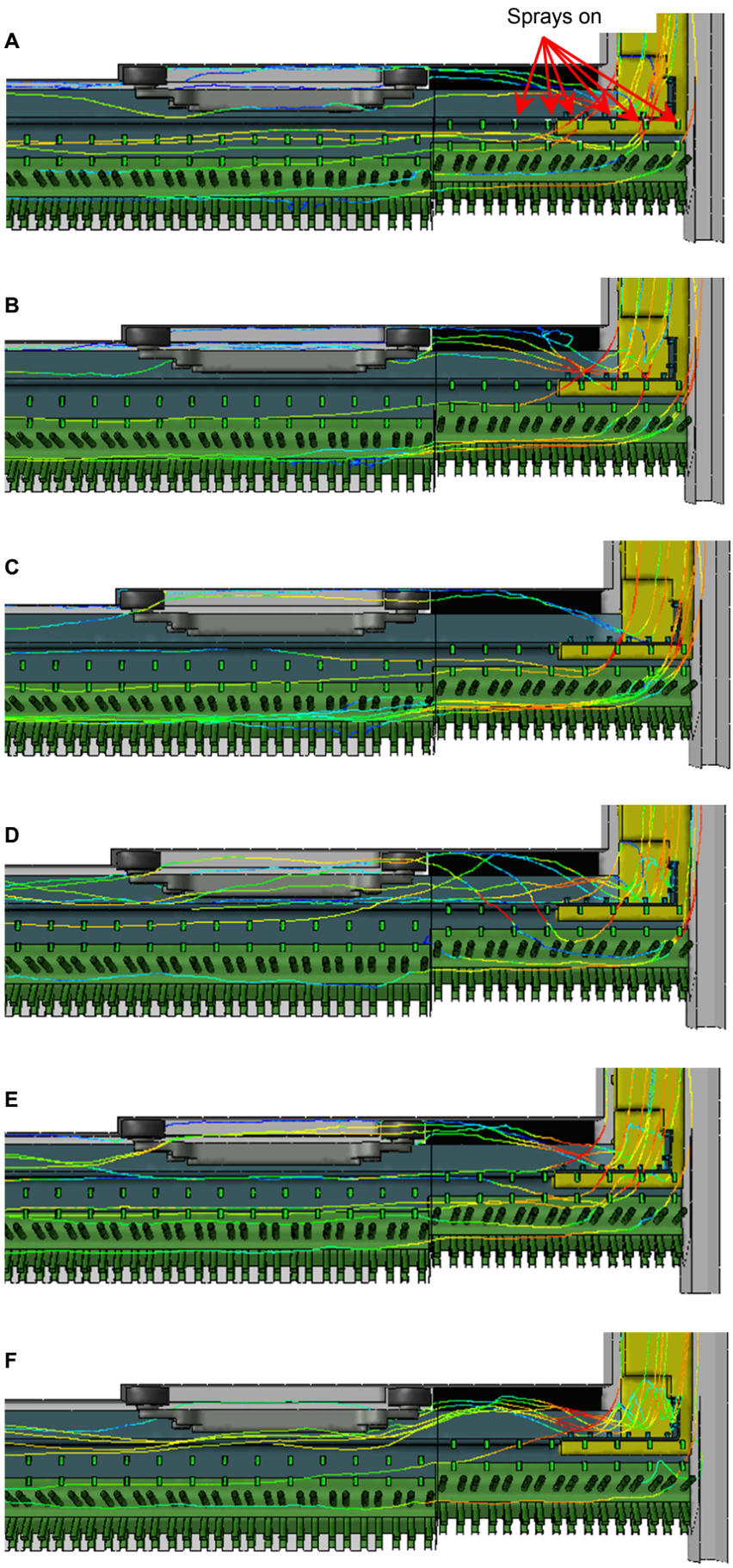

FIG 12 - Operation of venturi units at different orientation for longwall dust suppression (Ren *et al*, 2012b). (A) Operated at level and perpendicular to face; (B) operated at level and tilted 20° along face; (C) operated at level and tilted 45° along face; (D) operated at 20° down and 30° along face; (E) operated at 20° down and 45° along face; (F) operated at 30° down and 20° along face.

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