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CFD MODELLING OF THE DUST AND AIR VELOCITY BEHAVIOUR AT AN UNDERGROUND COAL MINE ROADWAY

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Keywords

Respirable dust,
Air velocity,
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Coal mine,
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Abstract

Dust pollution for ventilation systems is a big problem for mine workers in underground coal mines. The respirable dust concentration is important to the physical and spiritual health of miners. It is hazardous up to 2 mg/m^{3}in the air in underground coal galleries. In the present work, the airflow velocity and dust concentration values were measured at Çay 1-Kartiye roadway in Kozlu, Zonguldak. The goal of this research is modelling to the dust concentration and airflow velocity values by the computational fluid dynamics (CFD) method. An airflow and dust fluid and solid model was done using the Eularian-Granular multiphase method with the k-epsilon two-equation model. The results showed that dust concentration values were too low and fixed. The error percentage of airflow velocity values changed between 5% and 17%. Thus, this roadway is safe for coal dust explorations.

BİR YERALTI KÖMÜR MADENİ GALERİSİNDE TOZ VE HAVA HIZI DAVRANIŞININ CFD İLE MODELLENMESİ

Anahtar Kelimeler

Solunabilir toz
Hava hızı
CFD modelleme
Kömür madeni
Madenlerde iş güvenliği

Öz

Havalandırma sistemlerinde toz kirliliği, yeraltı kömür madenlerinde maden çalışanları için büyük bir problemdir. Solunabilir toz konsantrasyonu, madencilerin fiziksel ve ruhsal sağlığı için önemlidir. Bu değer, yeraltı kömür madenlerindeki havada 2 mg/m^3 üzerinde tehlikelidir. Bu çalışmada, hava hızı ve toz konsantrasyon değerleri Kozlu (Zonguldak) Çay-1 Kartiye galerisinde ölçülmüştür. Bu çalışmanın amacı, hesaplamalı akışkanlar metodu (CFD) ile toz konsantrasyonu ile hava hızını modellemektir. Bir hava akış-toz çift sıvı-katı modeli, k-epsilon iki-denklem modeli ile Eularian-Granular çoklu faz metodu kullanılarak yapılmıştır. Sonuçlara göre; toz konsantrasyon değerleri çok düşük ve sabittir. Hava hız değerlerinin hata yüzdesi % 5 ile % 17 arasında değişmiştir. Bu sonuçlara göre, bu galerinin kömür tozu patlamaları açısından emniyetli olduğu söylenebilir.

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1. Introduction

Coal is the most important energy source and will remain in the future. However, an underground coal mine is the most dangerous working area for miners since gas and dust explosions. Dust explosions are a process of combustible dust. The parameters influencing dust explosions are the particle size (distribution), the chemical properties of the dust, the initial and boundary conditions, the fuel-to-air ratio in the dust clouds, the turbulent flow conditions and the geometry of the process equipment (Ghaffari, Hoffman, Skjold, Eckhoff and Wingerden, 2019). Significant dust amount occurs during roadway development, longwall faces, and heading faces. The upper dust concentration can result in a coal dust explosion and spontaneous combustion in mines. 87.32 % of China's 532 coal mines are dangerous for coal dust explosions according to statistics (Hu, Liao, Feng, Huang, Shao, Gao, and Hu, 2020). Additionally, dust is a reason for the black lung disease in the U.S. and Australian coal mines. In China, 777.173 pneumoconiosis cases occurred in 2014 and 26.730 new cases in 2016. (Wang, Li, Ren, Wu, Lin, and Shuang, 2019).

To effectively reduce dust-related accidents and the impact of dust on the health of workers, measures are taken during the mining process such as coal-seam water injection, physical chemistry prevention, spraying, foam and ventilation (Wang, Luo, Geng, Li, and

Li, 2015). A good ventilation system is mandatory with the regulatory limits for safety and cost. A ventilation system accounts for up to 60% of the total operating cost. The high cost is needed for the power to supply the airflow in the mine (Candra, Pulung, and Sadashiv, 2014).

In Turkiye, the first regulation was issued about dust control in 1990. The Turkish Hardcoal Enterprise (TTK) has the biggest coal basins in Zonguldak (Fig.1) (Can, Kuşçu, and Mekik, 2012). It has five collieries, namely Kozlu, Amasra, Armutçuk, Üzülmez and Karadon (Erol, Aydin, Didari, and Ural, 2013).

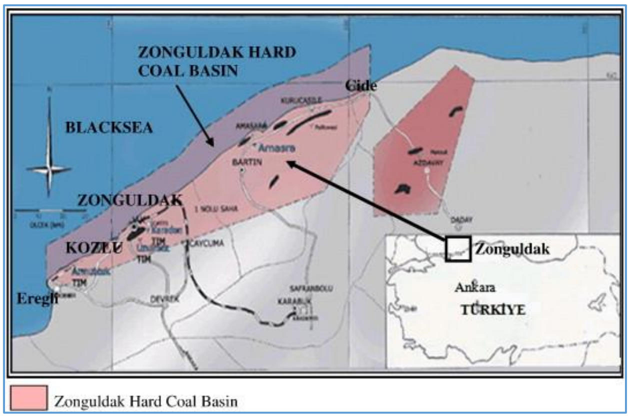


Fig.1. Geological Map of Zonguldak Coal Mines

Workplace respirable dust level monitoring was started in 1977 in Zonguldak coal basin. The threshold limit value (TLV) is limited to 5,0 mg/m³ for respirable coal mines. The respirable dust concentration changes from 1,6 to 14,5 mg/m³ in the coal faces of TTK (Erol, Aydin, Didari, and Ural, 2013). A typical curve of the relationship between air velocity and dust concentration in roadways is shown in Fig. 2 (Ren, Wang, and Cooper, 2014).

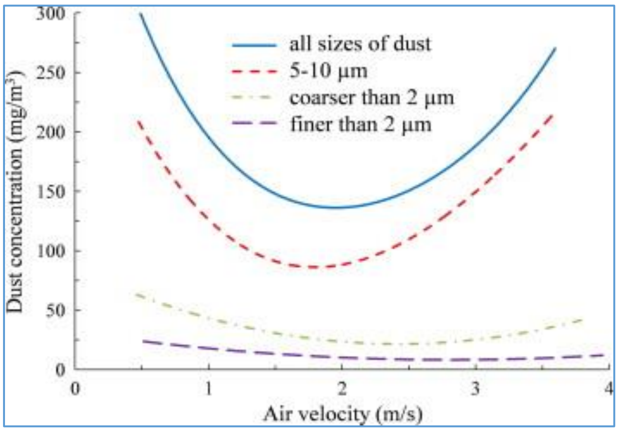


Fig.2. Graph of Trend Between Air Velocity and Dust Concentration.

In recent years, the Computational Fluid Dynamics (CFD) method has been commonly used to model underground mine applications. The studies in underground mines include; mine ventilation airflow patterns and recirculation of return into intake air, control of coal spontaneous heating and the dust, fire, optimization of gob inertization, methane management, measurement of turbulent diffusion, transit flow times through stopped areas, the effectiveness of auxiliary fans, estimation of volumetric flow rates and air leakage (Xu, Jong, Luxbacher, Ragab, and Karmis, 2015). Additionally, optimal conditions are suggested in the field of optimal design process. From an economical perspective, the CFD is an important tool for less energy consumption and costs of operating the fans and ventilation systems. This study is related with application of CFD method to an actual coal mine roadway.

2. Literature

Numerical models are effectively preferred to the gas-solid flow trends in coal mine roadways. Since the 1990s, the Computational Fluid Dynamics (CFD) method has effectively become common in solving problems of multiphase flow such as dust diffusion flow. The airflow behaviour affects the diffusion of dust particles and shows the dust problem in coal mines. Torano et al. researched dust behaviour and airflow velocity in two auxiliary ventilation systems by CFD methods. High dust concentration values were found in the zone of the road header loading and the vicinity of the machine operator (Torano, Torno, Menendez, and Gent, 2011). Ren et al. applied a new dust movement system in underground longwall faces, gallery and tunnel excavations by road reader. According to the results, respirable dust particles were reduced by up to 68% in the vicinity of the underground storage and 40% along the belt gallery (Ren, Wang, and Cooper, 2014). Zhou, Zhang, Bai, Fan and Wang (2017) modelled dust behaviour in Tongkou coal mine of the Zibo Mining. The average speed of respirable dust accessed to 91.06% in working areas. Yu, Cheng, Wu, Wang, and Xie (2017) modelled dust particles according to the k-epsilon two-equation turbulent model and the Hertz-Mindlin model by CFD-DEM simulation. Two top-speed airflow regions were composed in the vicinity of the tunnel floor and roof. Dust particles exhibit the same dust emission trends. Geng, Luo, Zhou, Zhao, Ma, Chai and Zhang (2017) studied the dust dispersion with Euler-Euler and the Euler-Lagrange methods in underground coal mines. Dust particles differ in different sizes. Prostanski (2015) developed a model about the dust in a protective zone of a longwall in Brzeszcze coal mine. Wang et al. (2019) detected respirable dust pollution properties by the CFD model in an underground heading face driven. Geng, Luo, Wang, Peng, Hu, Zhang, and Chai (2018) modelled dust contamination in ventilation systems during underground coal mining. Zhang, Zhou, Qian, Yuan, Sun, and Wang (2018) simulated to spread behaviour properties of the respirable dust of a fully-mechanized face in Daliuta coal mine ventilation conditions under negative pressure. According to the results, a top-speed zone is shaped among the coal shearer and hydraulic pillars (Zhang et al., 2018). Hu et al. (2020) modelled ventilation velocity by the CFD method in coal mine roadways. In a result, the dust dispersion had decreased behind the road headers due to decreases in the airflow velocities. Wang et al. investigated the dust movement by the CFD method in a mechanized heading face (Wang, Luo, Geng, and Li, 2015). Wang and Ren (2013) simulated to diminish dust contamination in the air with the 3D CFD method in an underground coal mine. Stovern et al. modelled the dust transportation and emissions in the Iron King Mine tailings (Dewey-Humbolt, Arizona) to the surrounding region by the CFD method. According to the results, wind velocity profiles and the local topography are the main parameters in the model simulations (Stovern, Felix, Csavina, Rine, Russell, Jones, King, Betterton, and Saez, 2014). Xia et al. modelled the ventilation and dust suppression system by CFD in open-type TBM tunneling areas (Xia, Yuan, Hu, Wu, and Han, 2016). Candra, Pulung, and Sadashiv (2014) evaluated to movement of dust dispersion from the mining face by the CFD method. They used to combination of blowing and exhausting fans (Candra et al., 2014). Hurtado and Acura (2015) estimated the airflow volume of fans by CFD in the parallel installation in El Teniente Mine in Rancagua, Chile. Guo and Zhang (2014) modelled the critical velocity using CFD and FDS programs for tunnel fire under longitudinal ventilation. Sasmito, Birgersson, Ly, and Mujumdar (2013) predicted the dust in a room and pillar texture in an underground coal mine by CFD software. Air quality, quantity and cost of the ventilation system were represented (Sasmito et al., 2013). Torno, Torano, Ulecia, and Allende (2013) developed 4D models by CFD for blasting gas property in auxiliary ventilation of galleries (Torno et al., 2013). Xu, Luxbacher, Ragab, and Schafrik (2013) modelled the airflow and tracer distribution by CFD in an underground mine (Xu et al., 2013).

This study aims to investigate air velocity and dust behaviour in an underground coal roadway via Ansys-16.00 to improve the ventilation system and diminish the cost. The Euler granular method was used for gas and solid two-phase flow with the k-epsilon turbulence model. The modelling and measured results were compared with each other.

3. Study Area

The Çay V Kartiye 1 coal seam is a drift in the Kozlu coal basin in Zonguldak, Turkey. It has a 3 m. seam thick at a depth from the surface of 425/-930 m. and has a 215095 ton reserve. The coal gallery is 485 m. long (Fig. 3). The slope of the seam is 10^0. It has a longwall caving mining method and wooden support. The coal heading is 485 m. long. The ventilation duct is fixed at 130 m from the gallery inlet.

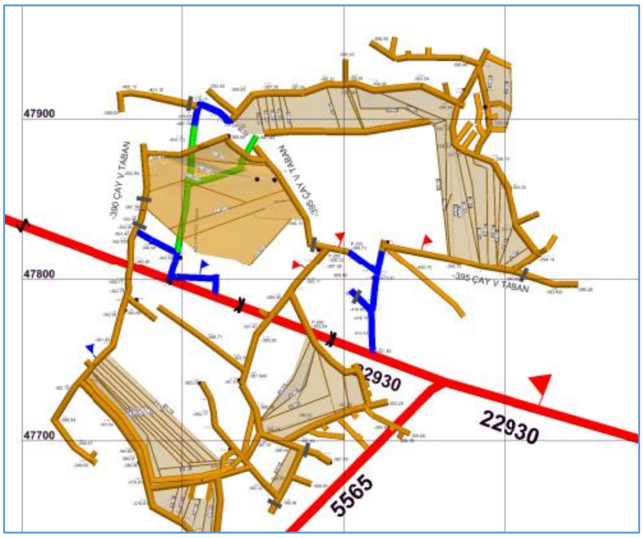


Fig. 3. The Çay V Kartiye-1 Coal Seam Plan.

Two fans were placed at 130 m. far from the entry. The forcing fan has 40 HP and the exhausting fan has 25 HP with a diameter of 600 mm. Dust measurements were taken with a dust sensor every day. The air velocity values were taken from the establishment. Inlet and outlet air velocity values were measured as 0.6 m/s.

4. Mathematical Model

Dust movements involve a gas-solid two-phase flow in a coal roadway. Two-phase flow is divided into the Euler-Euler and the Euler-Lagrange methods. The solid phase is continuous-phase in the Euler-Euler method. The solid phase is a dispersed-phase in the Euler-Lagrange method. Particles are examined in the particle phase (Geng, Luo, Zhou, Zhao, Ma, Chai, and Zhang, 2017).

4.1. Turbulence Model

The Reynolds number (Re) of airflow $>1x10^6$, so the airflow is turbulent flow in the roadway. The model has the following assumptions: 1) the airflow is incompressible, 2) heat and mass transfer are disregarded, 3) the gravity is activated by 9.81 m/s^2 and 4) the continuum is under the assumption. The continuity equation of the airflow was in Equation 1 (Hu et al., 2020).

$$\frac{\partial \rho}{\partial t}+\frac{\partial (\rho u_i)}{\partial x_i}=0 \tag{1}$$

Where; ρ is the density (kg/m^3), u_i represents the air velocities for the x,y,z directions (m/s) and x_i presents the coordinates in the x,y,z directions (m). The momentum equation of the airflow was in Equation. 2 (Hu et al., 2020).

$$\frac{\partial}{\partial t}(\rho u_i)+\frac{\partial}{\partial x_j}(\rho u_i u_j)=-\frac{\partial \rho}{\partial x_i}+\frac{\partial}{\partial x_j}\left[(\mu+\mu_t)\left[\frac{\partial u_j}{\partial x_i}+\frac{\partial u_i}{\partial x_j}\right]\right] \tag{2}$$

Where; ρ is the effective pressure of the turbulent flow (Pa), μ is the laminar flow viscosity coefficient (Pas), μ_t is the turbulent viscosity coefficient (Pas). The k-equation was in Equation 3 and the ε- equation was in Equation 4.

$$\frac{\partial(\rho k)}{\partial t}+\frac{\partial(\rho k u_i)}{\partial x_i}=\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{u_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right]+G_k-\rho\varepsilon \tag{3}$$

$$\frac{\partial(\rho \varepsilon)}{\partial t}+\frac{\partial(\rho \varepsilon u_i)}{\partial x_i}=\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{u_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right]+\frac{C_{1\varepsilon}\varepsilon}{k}\left[\mu_t\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right)\frac{\partial u_i}{\partial x_j}\right]-C_{2\varepsilon}\rho\frac{\varepsilon^2}{k} \tag{4}$$

Where; ε is the dissipation velocity of kinetic energy of the turbulent (m^2/s^{-3}), k is the turbulent flow momentum (m^2/s^2), $C_\mu=0.09$, $\sigma_k=1.00$, $\sigma_\varepsilon=1.30$, $C_{1\varepsilon}=1.44$, $C_{2\varepsilon}=1.92$ (Hu et al., 2020).

In Equation 5 and 6, dust particles are solved using the momentum equation.

$$\frac{du_p}{dt}=F_D(u-u_p)+\frac{g(\rho_p-\rho)}{\rho_p}+F \tag{5}$$

Where; u_p is the particle velocity vector, ρ and ρ_p are the density of fluid and particles (Ren et al., 2014).

$$F_D=\frac{18\mu}{\rho_p d_p^2 C_C} \tag{6}$$

Where; F_D is the drag force, C_C is the slip correction factor, d_p is the diameter of the particle and μ is the fluid's viscosity (Stovern, Felix, Csavina, Rine, Russell, Jones, King, Betterton, and Saez, 2014).

4.2. Computational Method

The airflow and coal dust dispersions were modelled as gas and solid two-phase flow. The steady solver, Standart k-ε two-equation model, k-epsilon viscous model and the SIMPLE algorithm were selected.

4.3. Boundary Conditions

There are three boundary conditions. They are inlet, outlet, and wall. The inlet of airflow is measured as 4.5 m3/s at the forcing duct inlet and the outlet is 7.5 m3/s. The velocity-inlet is 0,5 m/s and the outlet is 0 Pa pressure-outlet in modelling. Wall is a no-slip boundary condition. The standard wall function was used at walls. Species were prescribed to zero. The temperature was 3000 K. The meshing of the model is carried out in the Ansys-16.00 program, achieving 174939 hexahedral cells and 222451 nods (Fig.4). The direction of flow was chosen along the Z-axis. The mesh quality is found 0,56. It is high quality because of closer to 0,8.

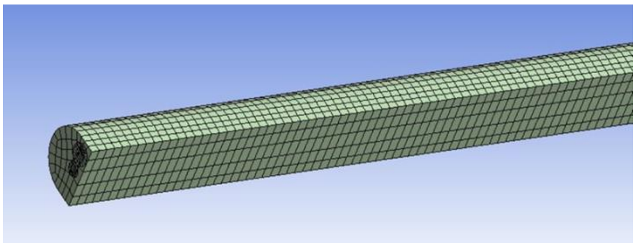


Fig. 4. Meshing of the Çay V Kartiye-1 Roadway.

5. Results

5.1. CFD Modelling of Air Velocity Behaviour

Lower airflow velocity zones are dangerous for gasses and dust accumulation. Thus, the airflow velocity should be measured in the gallery. The airflow velocity behaviour of the wall is 0 m/s because of no-slip boundary conditions in this model. The airflow behaviour contours of cross-section Z are shown in Fig. 5a-b.

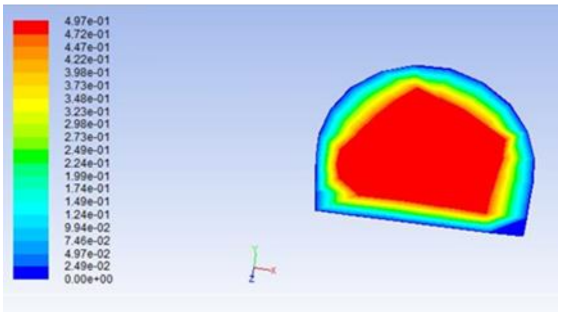
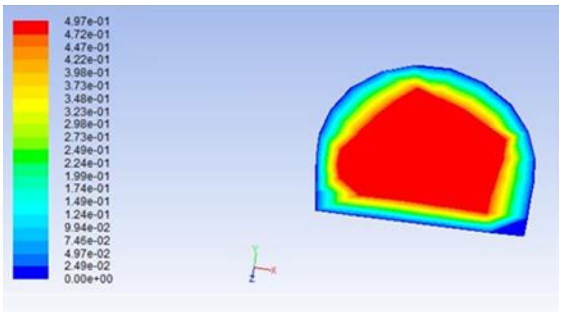


Fig. 5. a.) Contours of Airflow Inlet Velocity.



b.) Contours of Airflow Outlet Velocity.

According to modelling, the air velocity has a maximum value (0.497 m/s) in the inlet cross-section of the gallery. It decreases from the center to the gallery wall because of dust accumulation (Fig. 5a). The center of air velocity in the outlet cross-section of the roadway (0.571 m/s) is bigger than the center of air velocity in the inlet cross-section of the gallery (Fig. 5b). Velocity magnitude and pathlines of airflow are shown in Fig. 6 and Fig. 7.

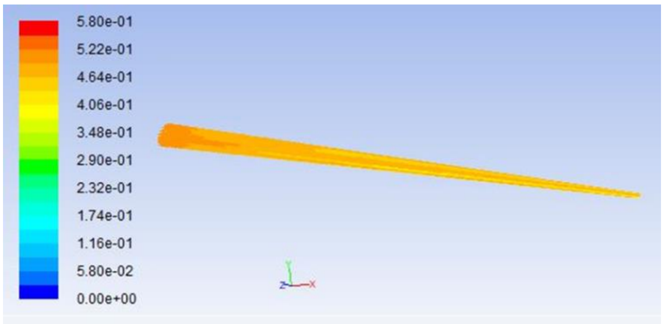


Fig. 6. Velocity Field of Air Flow.

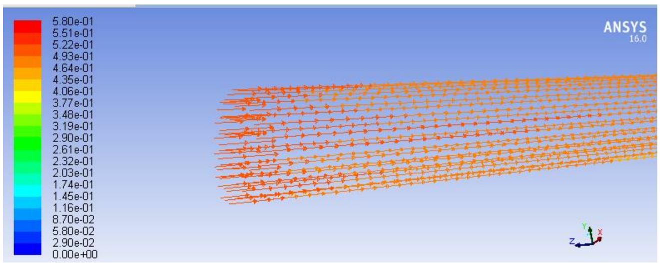


Fig. 7. Pahlines of Air Flow.

The air goes from the ventilation duct to the mining face (Fig. 6). The air velocity has a maximum value (0.58 m/s) and slightly increases to the outlet.

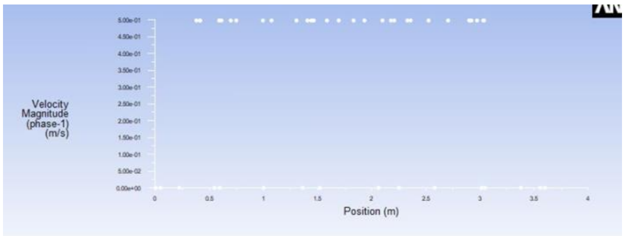


Fig. 8. Graph of the Airflow Inlet Velocity.

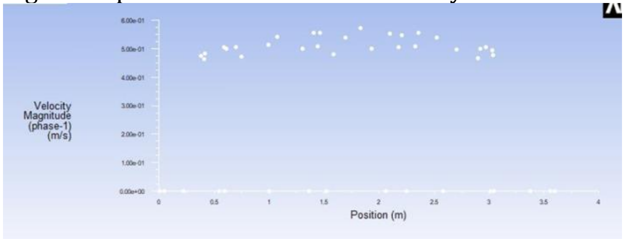


Fig. 9. Graph of the Airflow Outlet Velocity.

Airflow inlet velocity value is fixed (0.5 m/s) and airflow outlet velocity changes between 0.5 and 0.6 m/s (Fig.8-9). CFD and measured velocity values are compared in Table 1.

Table 1. Evaluation of Relationship Between the CFD and Measured Velocity Data.

Velocity (m/s**)**	Measured (m/s)	Modeling (m/s**)**	Error **(%)**
İnlet	0.6	0.6	17.17
Outlet	0.6	0.571	4.83

According to compared CFD and measured results, the inlet air velocity error is 17.17% and the outlet air velocity error is 4.83%.

5.2. CFD Modelling of The Respirable Dust Flow Behaviour

High dust concentration mainly gathers near the mining face, the roof and the top of the shearer (Zhou et al., 2017; Geng et al., 2018). Additionally, the length of the exhaust ventilation duct impacts dust dispersion (Geng, Luo, Wang, Peng, Hu, Zhang, and Chai, 2018). Dust concentration density is shown in Fig. 10.

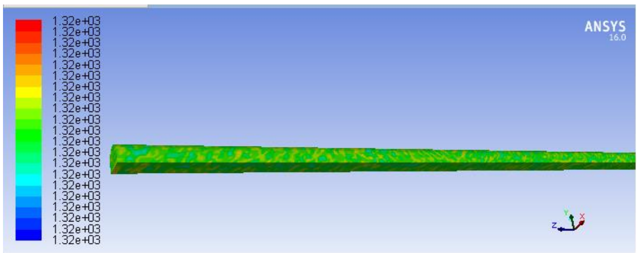


Fig. 10. Contours of Dust Concentration (kg/m^3).

The dust concentrations were observed in the stable region. Dust dispersion occurs as an equal result of blowing and exhaust fans (Fig. 10). CFD dust concentration values were found as 0.0132 mg/m^3. Thus, measured and modelling values are equal to each other.

6. Conclusions

The standard deviations of the model and measured values of the air velocities and dust concentrations behaviours were examined in this study. The results are summarized as below:

1) The airflow and turbulence are the key parameters to affect the dust dispersion. Two parallel fans were supplied to be less resistant and have more airflow. The difference between modelled and measured values can be explained by two factors: turbulence and shock losses. Additionally, losses will impact the fan's performance. The errors in the airflow velocity between the modelling and measured values were 4.83% and 17.17%. Airflows were displayed fewer increases to the outlet.

2) The dust mainly occurred by the shearer and the road header. The advancing support pollutes the mining area. Pollutants accumulate in the low-velocity zones and recirculation areas. Modelling and measured dust concentration values were found equal to each. This is an insignificant value (0.0132 mg/m^3) for dust hazards in the mine because it is so far below the limit safety value. Dust concentrations were under the limit due to sufficient ventilation and the position of fans. Thus, there isn't dust movement in the coal roadway.

3) There were no high-temperature heat sources such as coal mining machinery and shearer equipment. This condition has a positive effect on dust accumulation. Because the mine heat damage seriously affects the coal mine safety.

The computational fluid dynamics method shows an effective dust control system for personnel safety in the coal roadway. This approach is helpful for dust control in the coal roadways.

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