11 Jun 2008

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## Recommended Citation

Y. Zheng and J. C. Tien, "DPM Dispersion Study Using CFD for Underground Metal / Nonmetal Mines," *Proceedings of the 12th U.S./North American Mine Ventilation Symposium (2008, Reno, NV)*, pp. 487-493, Society for Mining, Metallurgy & Exploration Inc. (SME), Jun 2008.

*12th U.S./North American Mine Ventilation Symposium 2008 – Wallace (ed)*
*ISBN 978-0-615-20009-5*

# DPM dispersion study using CFD for underground metal/nonmetal mines

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Abstract: Diesel Particulate Matter (DPM) is considered carcinogenic after prolonged exposure. With increasing use of diesel-powered mining equipment in underground mines, miner's exposure to DPM has been increasing. Most studies on the issue has been DPM control measures with few studies on diesel exhaust propagation patterns after leaving the tailpipes. This study uses computational fluid dynamics (CFD) to investigate the airflow pattern in an underground metal/nonmetal mine for a single heading. Several high DPM concentration areas are identified in the study and common practices for compliance are suggested. Airflow and DPM distribution are compared between blowing and exhausting face ventilation systems. Suggestions are also provided for the protection of miners in the face area.

## 1 Introduction

Diesel-powered equipment is widely used in U.S. underground metal/nonmetal (M/NM) mines. According to a survey by the Mine Safety and Health Administration (MSHA), between 1998 and 1999, 196 out of 264 underground mines used 3,998 pieces of diesel equipment (Anon. 2001a). Diesel engines are reliable, fuel efficient, easy to repair, inexpensive to operate, and quite durable. It is not uncommon for diesel engines to have a life of 1,000,000 miles in heavy-duty trucks (Anon. 1999). Compared to electricity-powered equipment, diesel-powered equipment provide greater flexibility in underground travel routes with greater maneuverability and efficiency; it also provides more power and eliminates time-consuming battery change-out time compared to on-board battery-powered equipment (Anon. 2001b). Other hybrid electric or fuel cells power is not yet available for use on large equipment. Therefore, MSHA assumes that the underground M/NM mining community's significant reliance on diesel-power will continue (Anon. 2001a).

However, during the past two to three decades, the health effects of diesel emissions have received attention worldwide. It is believed that long-term exposure to diesel exhaust can be carcinogenic by several organizations (Anon., 1988; 2000 and 2001c). In addition, acute over-exposure to diesel exhaust has been linked to deleterious health effects such as eye and nose irritation, headaches, nausea, and asthma (Kahn and Orris, 1988; Rundell, et al., 1996; and Wade & Newman, 1993).

As a result, DPM regulations for underground M/NM mines were promulgated (Anon. 2001d). Current MSHA regulations require underground M/NM mine operators to control personal exposures to DPM to a permissible exposure limit (PEL) of 350 µg/m$^3$ of total carbon (TC) or less using the NIOSH 5040 method. Beginning May 20, 2008, mine operators must reduce miners' personal exposure to DPM to or below a PEL of 160 µg/m$^3$ of TC. This will have significant impacts on all M/NM mines that base their production on diesel equipment.

In a 2001 risk assessment study by MSHA, exposures from 355 samples collected at 27 underground M/NM mines, the mean DPM concentrations in the production areas and haulageways at those mines ranged from about 285 µg/m$^3$ to about 2,000 µg/m$^3$ of TC, with some individual measurements exceeding 3,500 µg/m$^3$. The overall mean DPM concentration was 808 µg/m$^3$ of TC. MSHA also collected 464 DPM samples at 31 underground M/NM mines in 2001 and 2002. Results based on 358 valid samples (from 30 mines) show that the mean concentration was 488 µg/m$^3$ of TC for metal mines, 372 µg/m$^3$ of TC for stone mines, 75 µg/m$^3$ of TC for trona mines and 287 µg/m$^3$ of TC for other mines.

MSHA's baseline sampling collected between October 30, 2002 and October 29, 2003 had a total of 1,194 valid samples from 183 mines. The mean TC concentration was 354 µg/m$^3$ for metal mines, 235 µg/m$^3$ for stone mines, 105 µg/m$^3$ for trona mines, and 195 µg/m$^3$ for others (Anon. 2005). During the time period from November 1, 2003 to January 31, 2006, 1,798 valid personal compliance samples from all mines covered by the regulation were collected. From these samples collected, 22% (396) of samples exceeded 350 µg/m$^3$ of TC, and 64% (1,151) exceeded 160 µg/m$^3$ of TC. These percentages show that miners are still being exposed to high levels of DPM (Anon. 2006).

Obviously, without further efforts, many of the underground M/NM mines will face difficulties in compliance with the final DPM limit.

MSHA summarized six available DPM control strategies. These strategies include the use of modern and low-DPM emission diesel engines, upgraded ventilation system, enclosed equipment cabs with filtered breathing air, administrative controls, alternative fuels, and DPM filters. None of those strategies is 100% efficient and experience show that a combination of several or all of the strategies will have to be implemented in the field in order to attain compliance.

Working in a confined underground space, ventilation is critical because eventually it is the ventilating air that carries the DPM out of the working area. For example, suppose only 1 gram is released into an underground environment, this amount can pollute 6,250 $m^3$ of space to the final 160 $\mu g/m^3$ if no ventilation is available.

Therefore, the first step in setting up a working face is to ensure there will be adequate air flow for the area. MSHA's "Work Place Diesel Emission Control Estimator" is a handy tool to determine DPM concentration for an underground mine (Haney and Saseen, 2000). If the results exceed the regulation limit under current condition, control strategies such as increasing main airflow quantity, use auxiliary ventilation, change to alternative fuels, etc. will have to be used. If different combinations of strategies are available to satisfy the existing regulations, the best strategy (or strategies) can be selected according to an economic evaluation. This is a common practice to control the DPM underground. But there are difficulties in carrying it out.

First, it is hard to measure the airflow in very low velocity areas (less than 0.25 m/s or 50 fpm), especially in many underground M/NM mines with large openings. If there are mining activities in those areas, the main airflow direction and quantity cannot be easily and accurately measured.

Second, MSHA model assumes DPM will be mixed uniformly in the face area, which may or may not be correct as it tends to flow upward or recirculate in the face area.

In this paper, CFD method will be used to evaluate the airflow before and after stopping installation in an underground metal mine in Missouri. This study shows that, although conditions are improved by stoppings, there are still places where ventilation is inadequate in the deep penetration of a long single heading without auxiliary ventilation. Results show that situation is much improved after an auxiliary fan and vent tubing are used.

Since the mass of any diesel particulate matters (up to 3,500 $\mu g/m^3$ from MSHA survey) is only a very small fraction of that of the air (1.2014 $kg/m^3$, standard condition), it is unlikely that they will have much effect on airflow distribution patterns. Therefore, it is assumed that DPM movement will be entirely dictated by the air flow pattern in this paper.

## 2 Main Airflow Simulation

A model was developed that depicts the south section of Doe Run Company's Buick Mine in Viburnum, Missouri. It is a highly mechanized room-and-pillar mining operation in a relatively flat-lying bed (Figure 1). The primary design of room widths are typically 9.8 m (32 ft), with pillar sizes at 8.5 by 8.5 m (28 by 28 ft). Thick ore zones are mined first using an initial pillar pass followed by a varied combination of back, bottom, undercut, and overcut passes, resulting in pillar heights ranging from 4 to 37 m (13 ft to 121 ft). In the study, the height is modeled with the typical value of 6.7 m (22 ft). The length of the south section is about 3.1 km (1.9 mi) by an average width of about 0.9 km (0.6 mi). As the operation goes on, some pillars with high grade ore are extracted and when it is economical, backfill is placed to allow for the extraction of additional pillars.

### 2.1 Main Airflow Simulation without Stoppings

As shown in Figure 1, there are two air shafts (1 and 2) in the south section of the mine, which is connected to the north by a single entry. Airshaft 1 is a return airshaft and has a fan with 25.5 $m^3/s$ (54, 000 cfm); Airshaft 2 is equipped with an intake fan providing 124.3 $m^3/s$ (263,300 cfm) of intake air for the mine. The single entry connecting the two sections has an airflow of 98.8 $m^3/s$ (209,300 cfm) traveling from south to north. Since more reserve has been found which extends the operation further south, the previously designed airshafts cannot provide adequate ventilation to remote face areas. This situation could be seen from Figure 2, where a 3D model of the south section was constructed. Simulations show that only the entries between the two air shafts can be ventilated by the main ventilation. Different colors of lines in Figure 2 represent the airflow traveling path in the underground space.

Figure 3 shows locations of concrete block toppings; No leakage is considered in this paper. Results are shown in Figures 4 and 5.

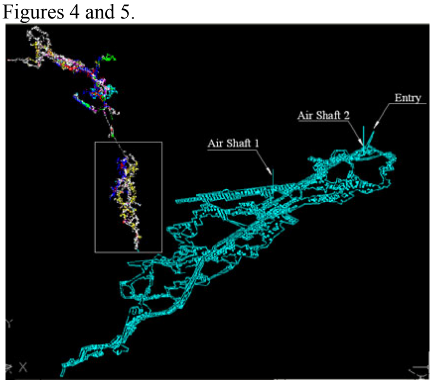

Figure 1. South section of an underground metal mine

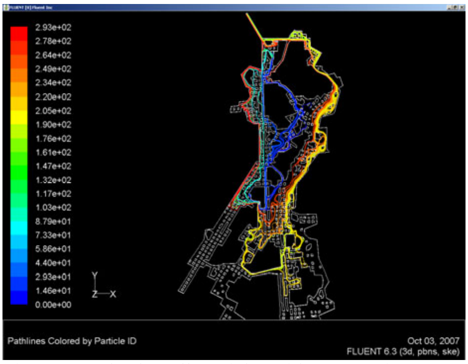

Figure 2. Path of small particles without stoppings.

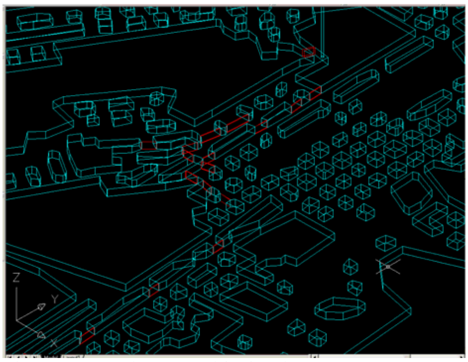

Figure 3. Stoppings to guide the air.

## 2.2 Main Airflow Simulation with Stoppings

Different colors lines in Figure 4 represent the traveling path of small (air) particles released from Airshaft 1, simulating airflow paths; entries that have color lines are ventilated by fresh air from Airshaft 1 and DPM produced in the area can be carried away by the main airflow. Simulation shows that most entries can be adequately ventilated using the fresh air from Airshaft 1 if effective stoppings are present as shown in Figure 4.

Although conditions are much improved by the addition of stopping lines, three types of areas still remain poorly ventilated as identified in Figure 5. Type I is a typical dead end heading; Type II is a cross cut; although there is evidence of airflow at both of its ends, the cross cut itself is not ventilated. Type III are places downstream of the backfill block; these places are inadequately ventilated if the main airflow cannot be guided by surrounding pillars or stoppings.

To solve or reduce DPM problems in the above three types of areas requires both adequate airflow in the main entry and auxiliary ventilation devices. The former requires effective and continuous stopping lines to deliver needed air quantity to the entrance of the long dead heading, while the latter requires proper placement of the auxiliary fan and tubing. This study concentrates on single heading ventilation.

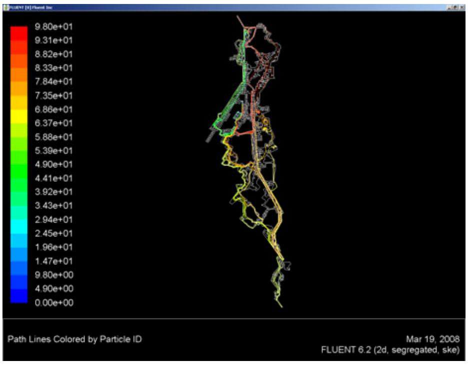

Figure 4. Path of small particles with stoppings.

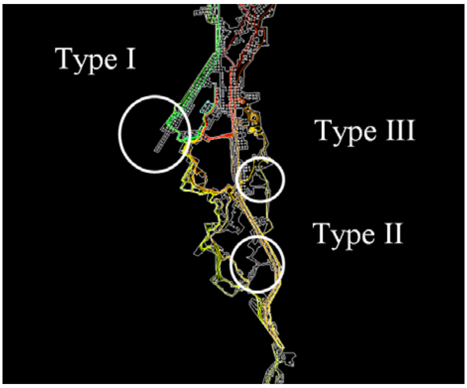

Figure 5. Three types of working face with ventilation problems.

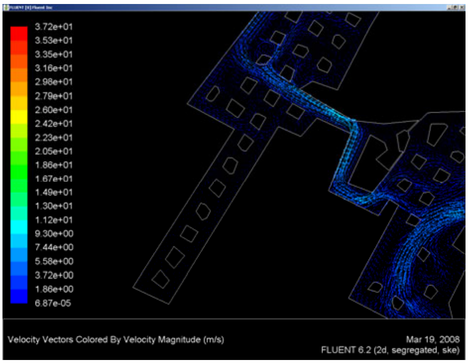

Figure 6. Main airflow velocity near the dead end opening.

## 3 Single Heading Air Flow Simulation

The single heading off the main entry measures 6.7 m (22 ft) x 9.8 m (32 ft) x 90 m (295 ft), height x width x length, respectively, with a short stub for facilitating traffic and loading on one side of the heading every 30 m (98 ft) (Figure 7 and 8). The vent tubing measures 80-cm (30 in.) in diameter.

Two types of face ventilation systems are evaluated. Figure 7 show the layout of a blower system and Figure 8 an exhaust system. In both cases, air in the main entry flows from bottom to top in the Figure. Therefore, the blowing fan should be installed on the intake side and the exhausting fan on the return side as shown in Figures 7 and 8.

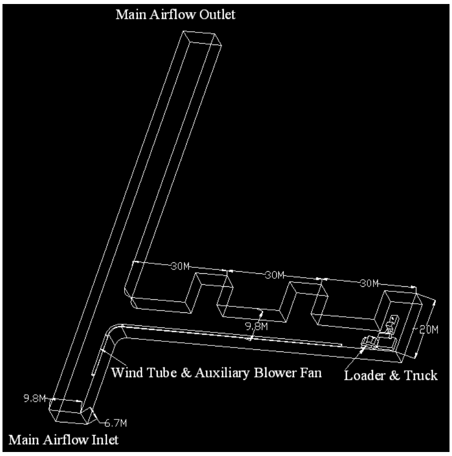

Figure 7. Layout of a single heading with blower fan and tubing.

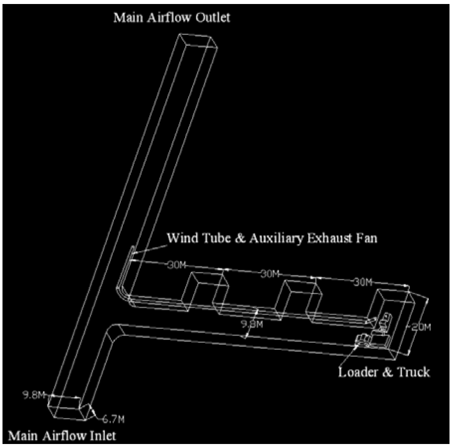

Figure 8. Layout of a single heading with exhaust fan and tubing.

The study models the worst situation in a typical operational cycle during a heading operation: drilling, blasting and mucking. Only loading and haulage equipment are considered because of the size of their diesel engines. The equipment for loading and haulage are a Caterpillar 725 articulated truck (Figure 9) and a 980H wheel loader (Figure 10); both are commonly used mining equipment in underground M/NM mines.

The fan in the study has a capacity of 14.2 $m^3/s$ (30,000 cfm) used in either a blowing or exhausting system. The air in the main entry has a constant speed of 1 m/s (197 fpm), which translates into a quantity of 65.6 $m^3/s$ (140,800 cfm). The exhaust velocity at the tailpipe of the loader and truck is set at 6 m/s (1,200 fpm) with temperature at 321 °C (610 °F), common in a typical heading operation (McGinn, 2004).

The steps required to conduct a CFD modeling exercise include the creation of a geometric model, mesh generation, establishing boundary conditions, running the simulation to solve the problem, and post-processing of results. The underground mine ventilation analysis in this paper was performed using FLUENT and its mesh generation software, GAMBIT. To create the geometric model of the mine and the single heading with loader and truck in operation, a 3-D modeling program Mechanical Desktop was also used.

Figure 9. A CAT 725 articulated truck.

Figure 10. A CAT 980H wheel loader.

## 3.1 Blowing System Simulation

Figure 11 shows the velocity vector of airflow in the main entry and the single heading with a blowing fan and the beginning of a 80-cm (30 in.) vent tubing; the tubing is extended 85 m (279 ft). As shown in the Figure, the air in the main entry enters the inlet of the blowing fan and the vent tubing, and then discharged into the face area with an average velocity of 28.3 m/s (5,569 fpm). It rapidly decreases to 2 m/s (394 fpm) after it travels between the end of the tubing and the end of the heading, bouncing around several times before traveling toward the main entry as it continuously loses speed (Figure 12).

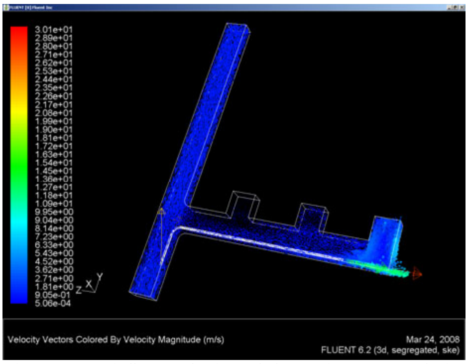

Figure 11. Airflow velocity of the main entry and single heading.

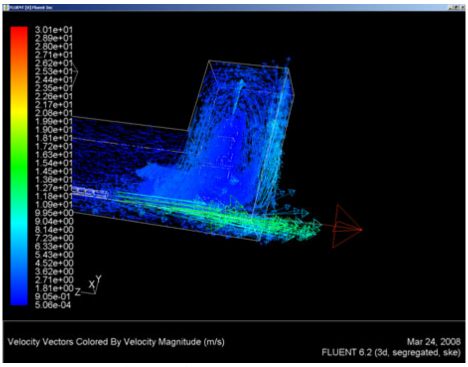

Figure 12. Airflow velocity in the face area.

Detailed velocity distribution in the face area is shown in Figure 12. The speed of the air from the end of the tubing decreases as it goes further from the tube outlet and dissipates more after each contact with the rib and is forced to change course, except when it is blocked by the truck, resulting in eddies in front of the truck. Eddies are also evident at all four sides of the loader. These eddies result from recirculated air from the vent tubing as demonstrated by the color path lines in Figure 13.

Figure 14 shows the DPM distribution in the face area with different colors expressing volume fraction of exhaust air — the fraction of exhaust air in a specific volume with the exhaust air volume fraction coming out of the tailpipe at 1 or 100%, decreasing as it moves further away from the tailpipe. As shown in Figure 14, a blowing face ventilation system can effectively clear the space between the rib and tailpipe and the driver's cab, although the space around the loader's cab indicates a slight DPM cloud but only at a volume fraction of less than 0.03. This translates to a concentration of 37.2 mg/m$^3$ of DPM per 100 bhp at the outlet of the tailpipe if no other control devices are used (e.g., filter). That means 130.2 mg/m$^3$ of DPM is produced at the outlet of a 350 bhp loader's tailpipe (130.2 mg/m$^3$ = 37.2 mg/m$^3$ × (350 bhp/ 100 bhp)), resulting in a concentration 3.9 mg/m$^3$ (130.2 mg/m$^3$ × 0.03) around the loader's cab area — 24 times that of the 160 µg/m$^3$ final limit. A DPM filter and/or environmental cab is needed for the loader. The truck driver and other persons outside of the loader should be fine.

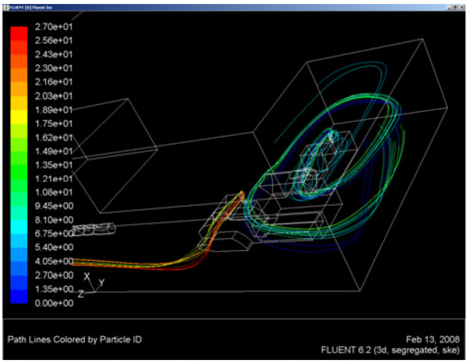

Figure 13. Exhaust airflow pattern in the face area.

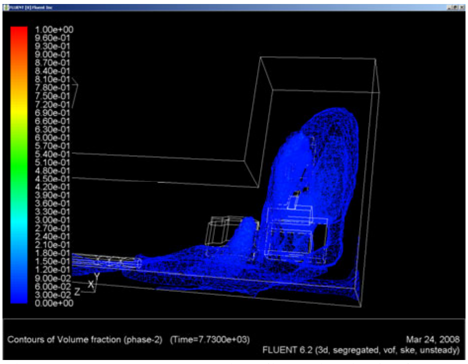

Figure 14. DPM concentration dispersion in the face.

### 3.2 Exhausting System Simulation

In an exhausting system (Figure 15), fresh air in the main entry is made to course through the single heading to the face area, then to the entrance of the exhaust tubing after mixing with dusts and DPM in the face area. The highest velocities (28.3 m/s or 5,569 fpm) occur at the entrance of the tubing, as shown in Figure 16. Although the quantity of fresh air flowing into the face remains the same as the blowing system, air velocities in the immediate face area is much lower. High velocity exhaust air at the exhaust tubing exit forms a jet stream that delivers the air quite a distance which keeps it from re-entering the single heading (Figure 17).

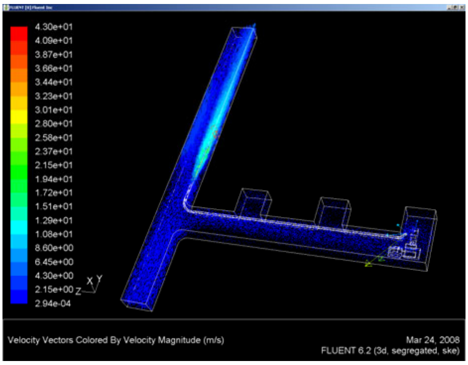

Figure 15. Airflow velocity of the main entry and single heading.

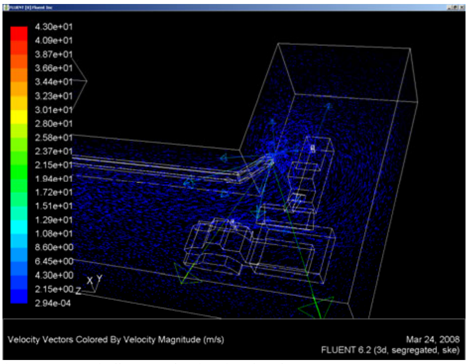

Figure 16. Airflow velocity in the face area.

Figure 18 details the traveling path of the exhaust flow (as represented by the color lines) from both the loader and the truck. Exhaust air from the tailpipes hits the rib and mixes with incoming fresh air, and then is sucked into the inlet of the exhausting tubing. The mixing process can be more clearly seen from Figure 19 where the DPM concentration is much higher and appears in most of the face area for the exhausting system than the blowing system, although the truck driver and miners working outside the immediate face area will have no DPM exposure as long as fresh air flows into the single heading.

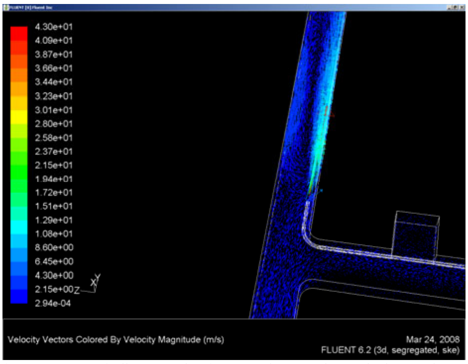

Figure 17. Airflow velocity at the outlet of the exhaust tubing.

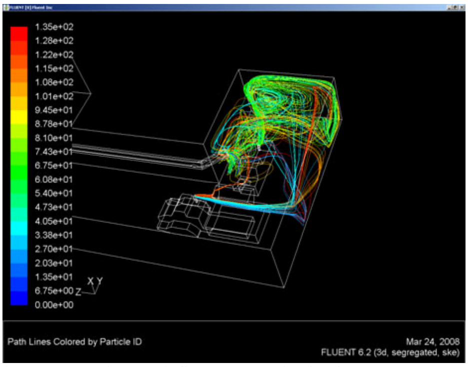

Figure 18. Exhaust airflow pattern in the face area.

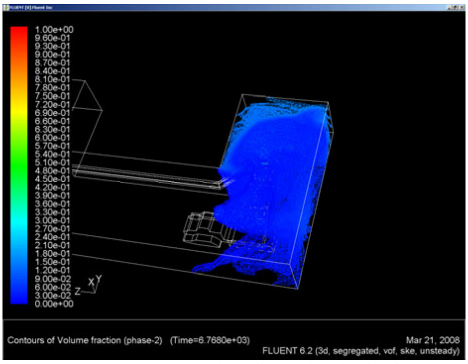

Figure 19. DPM concentration dispersion in the face.

## 4 Summery and Conclusions

This paper uses CFD to examine the airflow pattern in an underground metal mine and a long single heading. Poorly ventilated areas are identified and broadly categorized into three types. The study incorporated a typical single heading with a loader and truck operating in the immediate face area, and the use of both a blowing and exhausting with a tube. DPM concentration and propagation is also estimated under the assumption that DPM will follow the airflow underground. Study results are summarized as follows:

1. CFD methods can be an effective means to simulate the airflow patterns for the entire mine and for a single long heading, although the accuracy and detail of each depends on the accuracy of input data. Areas of poor ventilation can be identified and local ventilation control measures evaluated and designs assessed.
2. For a blowing face ventilation system, DPM is distributed in a much smaller space than an exhausting face ventilation system. In both systems, the loader driver in the cab is working in a high DPM environment. Effective strategies are needed to improve the situation.
3. DPM does not distribute evenly in the face area. High velocity fresh air tends to confine DPM in smaller area. High air velocity appears to be a more effective than quantity to control DPM.
4. For this model, the truck driver can work safely in either of the two face ventilation systems, although his environment will be significantly improved if located a little bit outside the immediate face area.
5. For the exhausting face ventilation system, the outlet of the tubing should be downstream away from the intersection of the main entry and the single heading to prevent intake and from mixing with the return air.

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