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Three-Dimensional Ventilation Modeling of a Large-Opening Stone Mine Using COMSOL Multiphysics

K.V. Raj
CDC NIOSH Pittsburgh Mining Research Division, Pittsburgh PA

Vasu Gangrade
CDC NIOSH Pittsburgh Mining Research Division, Pittsburgh PA

ABSTRACT

Airflow in large-opening stone mines is largely dependent on the natural ventilation due to the large cross- section area of the opening. The openings of such stone mines are typically twice or thrice the size of typical underground coal or metal/nonmetal mines. Due to the influence of natural ventilation, air velocities as well as the static pressure drop in the mines are low. Mines rely on auxiliary fans to ventilate active faces to reduce contaminant exposure to mine workers. The National Institute for Occupational Safety and Health (NIOSH) is conducting research on ventilation of large-opening stone mines to reduce worker exposure to dust and other contaminants such as diesel particulate matter (DPM). In order to reduce worker exposure to dust and DPM, an understanding of the airflow pattern due to auxiliary fans in the mine is needed. Under this research, NIOSH researchers are exploring the computational fluid dynamics (CFD) modeling to understand the airflow behavior in large-opening mines. In this paper, the team is presenting the results from three-dimensional CFD modeling of airflow in a large-opening stone mine and investigating the effect of a fan placement with the movement of trucks.

INTRODUCTION

Underground stone mines produce a wide range of material such as limestone, marble, sandstone, etc. for the construction industry that is needed for infrastructure development. As of 2020, there are 4,248 stone mining operations with 110 underground operations in the United States [1]. The majority of the underground stone mines produce broken limestone according to the standard industrial classification (SIC) system. These underground limestone mines are characterized by mine openings which are larger than the openings as compared to those of coal and metal/nonmetal mines. The mining method for large-opening limestone mines is room-and-pillar which is similar to coal mines. However, the dimensions of these underground mines are twice or thrice of the typical coal mines. The large openings and the inner dimension of the limestone mines creates a unique challenge to ventilate these mines. Due to the large dimensions, airflow in the mine is mainly influenced by natural ventilation with little differential pressure change at two locations in the mine. Due to the relatively small number of large opening mines not much attention was given to understand and address unique ventilation issue related to large-opening mines.

In the early 2000s, the National Institute for Occupational Safety and Health (NIOSH) started conducting research to improve air quality by reducing contaminants such as diesel particulate matter (DPM) in large-opening mines. These studies looked into ventilation, fan selection, stoppings, and mine planning to reduce the contaminants' level in large-opening mines [2]. The research suggested that large-opening mines face three primary ventilation challenges: moving adequate volumes of ventilation air, controlling and directing the airflow, and planning ventilation systems that work well with production requirements [3]. Multiple studies were also conducted that showed increased suitability of propeller fans for low-resistance ventilation systems present in stone mines compared to the vane axial fans commonly applied in coal mines [4, 5]. Studies on the effectiveness of different large- opening stone mine ventilation stoppings showed steel stoppings were effective for permanent stopping locations, fabric stoppings were more effective closer to blasting areas, and long stone pillars could perform the same role as a row of stoppings [6, 7]. Under this research, it was also found that movement of the loader and trucks lead to increase in airflow at the face, however, that increase is small [4, 7, 8]. Recently, researchers have conducted a field study of large-opening underground mines looking at variations in pressure, relative humidity, and temperature over time [9]. Past research, however, has not looked into numerical techniques to analyze the airflow patterns in large-opening mines. A numerical technique such as computational fluid dynamics (CFD) has been used for solving airflow problems in mine ventilation for quite some time. CFD modeling has been widely used in many areas of airflow and particulate and gaseous contaminant modeling from underground mine ventilation to open-pit ventilation [10–14]. Most recently, Gendrue and others [15] conducted CFD modeling to find a booster fan location in a large-opening mine. Watkins and Gangrade conducted a study using ANSYS Fluent to optimize the auxiliary fan placement in a large-opening stone mine [16]. Mohamed and others also presented a similar study using ANSYS Fluent for model airflow in a large-opening underground stone mine to aid the ventilation considering different stopping layouts [17]. However, these studies only looked at the fan placement and stopping layout. There are many commercially off-the-shelf and open-source CFD software programs, such as ANSYS Fluent, Cradle CFD, COMSOL Multiphysics, and OpenFOAM, that are available and being used to solve airflow problems in the mining industry. The majority of these CFD programs are based on Navier-Stokes equations, the energy equation, the mass conversion, and transport equations. CFD models have the potential to provide a pattern of airflow and contaminant concentration in large-opening underground stone mines.

The main focus of this study is to look at the impact of movement of truck on the ventilation. This study is a continuation of the work the authors published on two-dimensional modeling of a large-opening stone mine where they used the COMSOL Multiphysics® CFD modeling program to understand the influence of truck movement on airflow in mine [18]. The two-dimensional modeling study conducted by the authors did show that movement of truck lead to change in airflow in the mine, however, the two- dimensional modeling doesn't provide sufficient details of airflow patterns a three-dimensional modeling can provide. Therefore, this paper is on three-dimensional modeling of the mine geometry to better understand the airflow patterns with and without a fan and how the airflow pattern changes with the movement of a truck.

MODEL DESCRIPTION

The geometry for this work was adopted from Grau III and Krog [7] work to simulate the airflow inside the mine with four scenarios. The entry of the mine is 15.24 m, and the dimensions of the pillars are 15.24 m by 15.24 m. The extent of the model in the x-direction is 441.96 m, and in the y-direction it is 411.48 m. Figure 1 shows the plan view of the model geometry. This geometry was previously used for modeling airflow by the authors [18]. However, af er considering the influence of outside atmosphere on the ventilation of the mine, it was decided to modify the geometry to add outside atmosphere. To modify the geometry, an idealized condition was tested by adding a domain attached to the openings of the mine. The modified geometry is presented in Figure 2. The outside domain in the model geometry represents the atmosphere with the inlet at the top of the rectangular domain and the outlet at the bottom. The side boundary was treated as an open boundary condition to simulate the interaction with a large volume of air, i.e., atmosphere. Another reason to consider adding an outside domain was that the propeller fan near the opening of the mine is used to ventilate the mine and the assumption of using the main entry as an inlet (as in Figure 1) might not be a better approximation of airflow due to the fan near the opening. The dimension of the outside domain is 457-m long 122-m wide and 30-m high.

In this study, the team followed a similar strategy as in our previous paper [18] to look at the airflow without fan and with fan(s) in the model domain. After that, we simulated movement of a truck coming from the outside domain into the mine without any fan followed by simulating a fan with the movement of a truck. This strategy led the team to simulate four scenarios for this study.

Scenario 1: Model with no Fan

This modeling was done to understand the airflow pattern when no mechanical ventilation was used in the mine. This scenario serves as a baseline model to compare models with fan(s). Boundary conditions used for the model are inlet, outlet, interior wall, open boundary on top of the outside domain, symmetry, and wall. The inlet, outlet, and open boundary are as represented in Figure 2. The interior wall boundary represents the stopping as shown in Figure 1. The rest of the geometry represents the wall boundary. COMSOL Multiphysics has predefined mesh size settings from very coarse to extremely fine mesh size, and for the first scenario which is a simple model, we used a finer predefined mesh size setting where the mesh size ranged from 1.69 m to 14.3 m. The smaller size mesh is in the mine domain and the coarse mesh are in the outside domain.

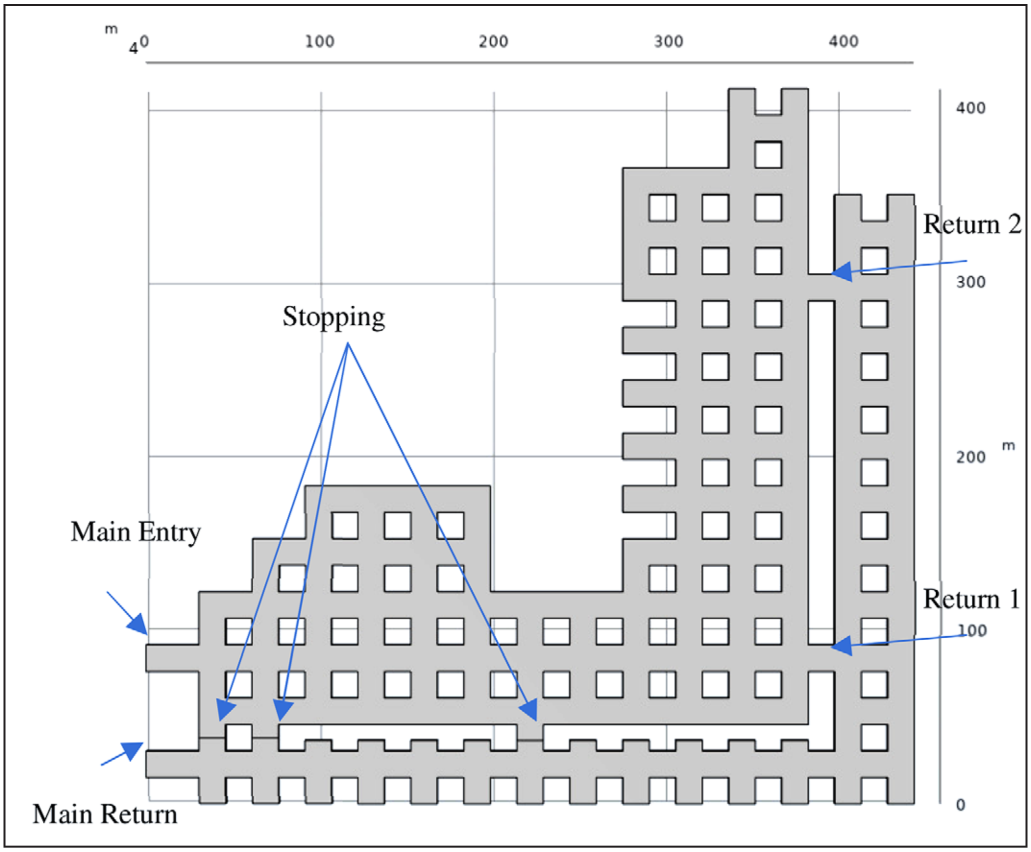

Figure 1. Geometry of the model domain (Grau III and Krog [7])

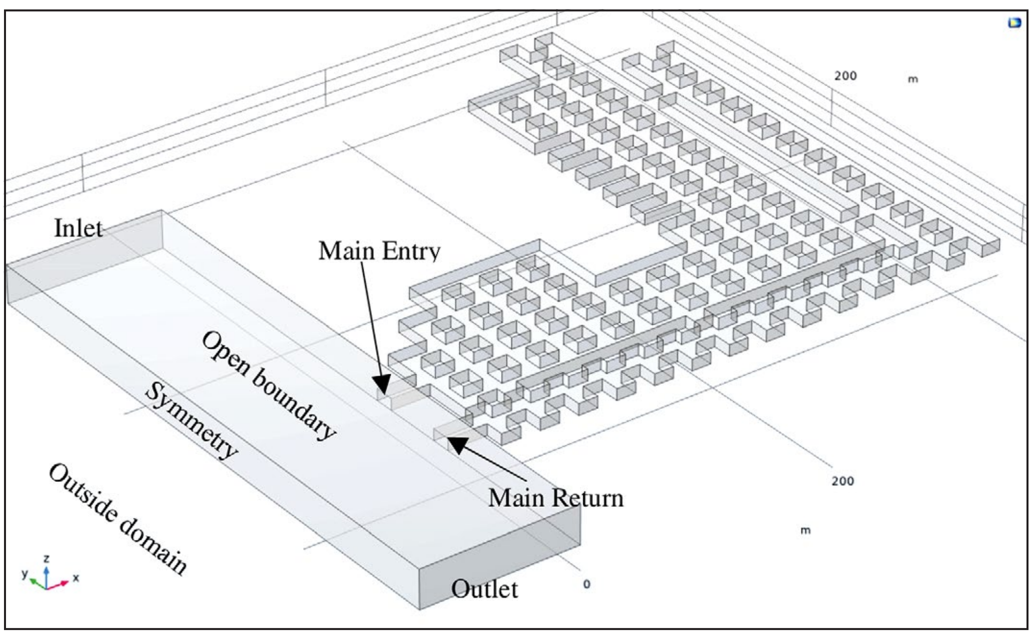

Figure 2. Modified geometry of the model domain with added outside domain

All mesh is triangular with boundary layer on the walls. Figure 3 shows the element size distribution of the triangular and boundary elements near the walls. The Realizable κ-ε turbulent model was used for all the simulation studies.

In this case, a steady state simulation was run with an inlet velocity of 0.5 m/s. The low velocity values represent a normal atmospheric condition when wind speed is low. Figure 4 presents the velocity profile along with streamlines at 0.5 m/s air velocity coming from the inlet. It can be seen from the streamlines that there is airflow inside the mine with extremely low velocities. The airflow is entering the mine from the main entry and coming out from the main

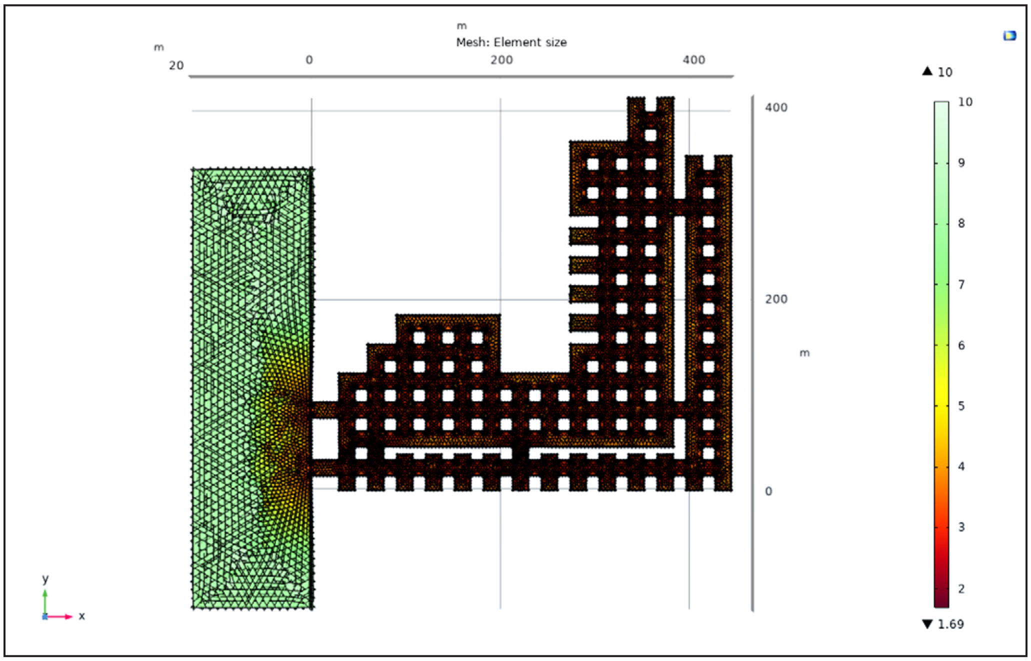

Figure 3. A view of the mesh size)in mm) in the model geometry

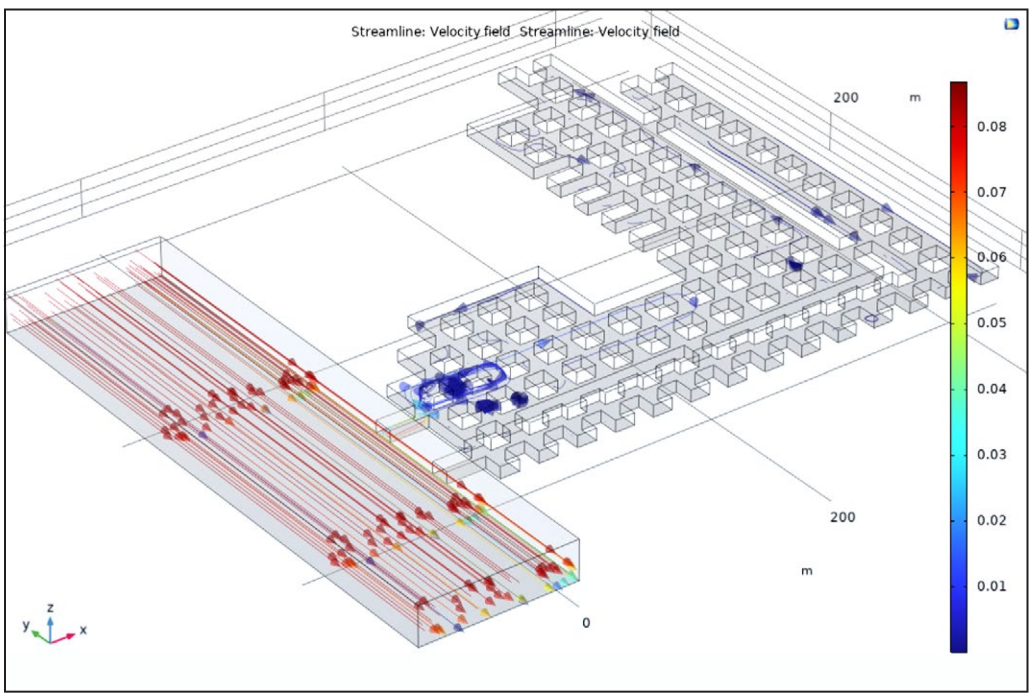

Figure 4. Velocity profile along with streamlines of the base model with an inlet velocity of 0.5 m/s

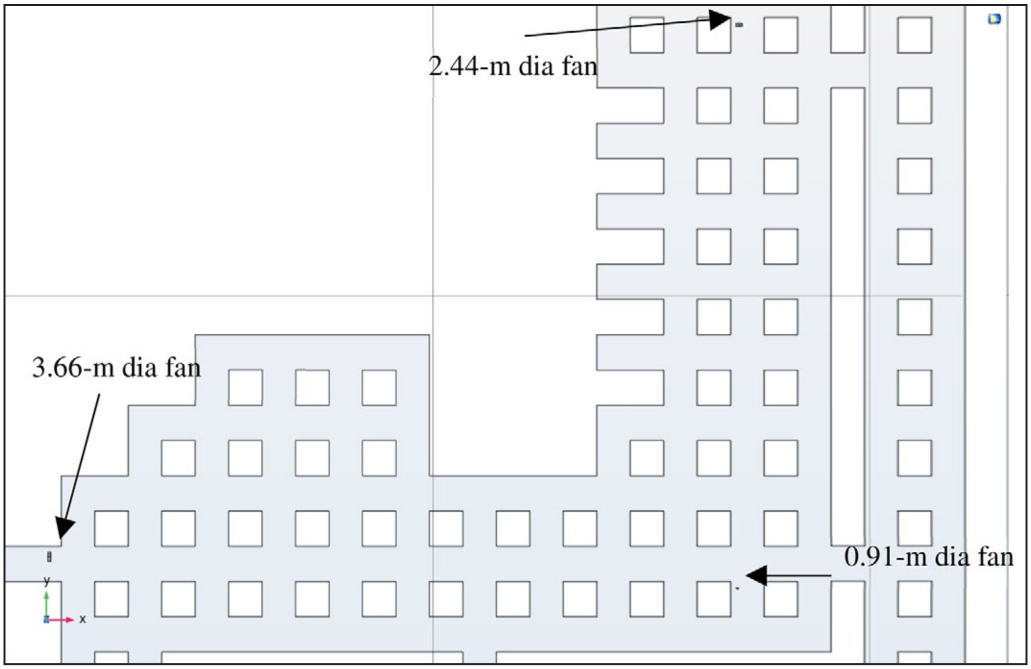

Figure 5. Fans located in the model domain

return. Air is recirculating near the entry as it enters the mine. This also shows that when there is no mechanical ventilation used at the mine, airflow is very low inside the mine.

Scenario 2: Model with Fan(s) in the Mine

In this scenario, fans were added to the base model with running them individually and in combination. The fan size and flowrates were adopted from previous work done by Grau III and Krog [7]. The location of the fans is shown in Figure 5. The 3.66-m diameter fan acts as the main ventilation fan in the mine which is 25 m from the mine entry. This fan was run individually and in combination with other fans to look at the effectiveness of

In order for better model convergence and resolution of flows, the mesh elements near the fans were created very fine. Figure 6 shows the mesh elements around the 3.66-m diameter fan. The model was run with a 3.66-m diameter fan in the model, and the velocity profile was plotted along with streamlines. It can be seen from Figure 7 that placing a mechanical means to ventilate the mine completely changes the airflow pattern inside the mine. In comparison to the velocity profile when no fan was placed in the mine, the airflow is following the path as observed in the work of Raj and Gangrade [18] when airflow is entering the mine entry and following the path of least resistance to get out of the mine return, even though there is some airflow near Return 2 but of very low velocity. This means that fresh air from the inlet is not being utilized by the fan, and due to recirculation contaminants like diesel particulate matter (DPM), dust and other engine exhaust concentrations might increase over time. This is the reason to have fans operating in combination to maximize ventilation. Grau III et al. (2002) also suggested that fan placement affects ventilation in large-opening mines. To this end, the two fans were placed in the mine domain and the combination of two fans in the model domain were the simulation to look at their effectiveness.

In order to compare the effectiveness of the simulation results, four locations were selected in the mine with three near Return 2 and one at the main return. Figure 8 shows the sampling locations for calculating the airflow quantities. Table 1 presents the airflow values at the four locations as shown in Figure 8. NIOSH also compared the airflow values from the base case when no mechanical means of ventilation was used in the first scenario. This is to show the change in airflow from the case where no fans are used to the cases when fans are used in the model domain. It can be clearly inferred from the table that when fans are used airflow in the mine increases. This increase in airflow quantity is, however, not same with all the fan combinations. The increase in airflow was mainly visible at the Location 1 (Return 2) with varying airflow at other locations near the working face. Locations 2 and 3 saw the highest increase in airflow with a 3.66-m and 2.44-m diameter fan combination in comparison to other fan configurations. These simulations show that proper fan placement and combination is needed for better airflow in the regions with low

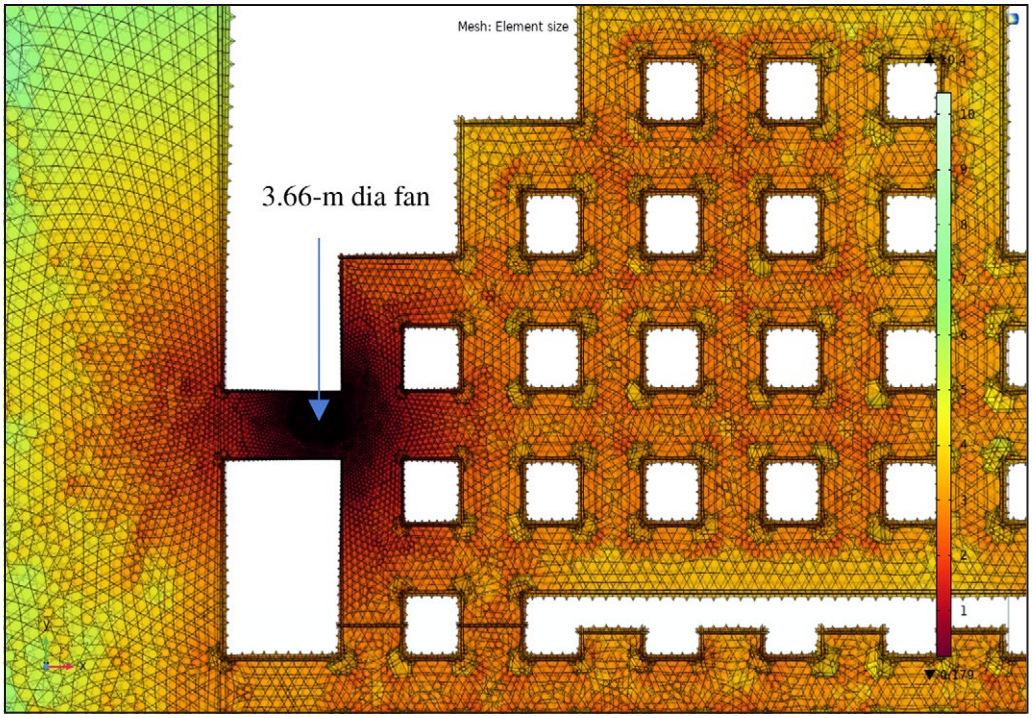

Figure 6. Fine mesh elements around the fan in the model

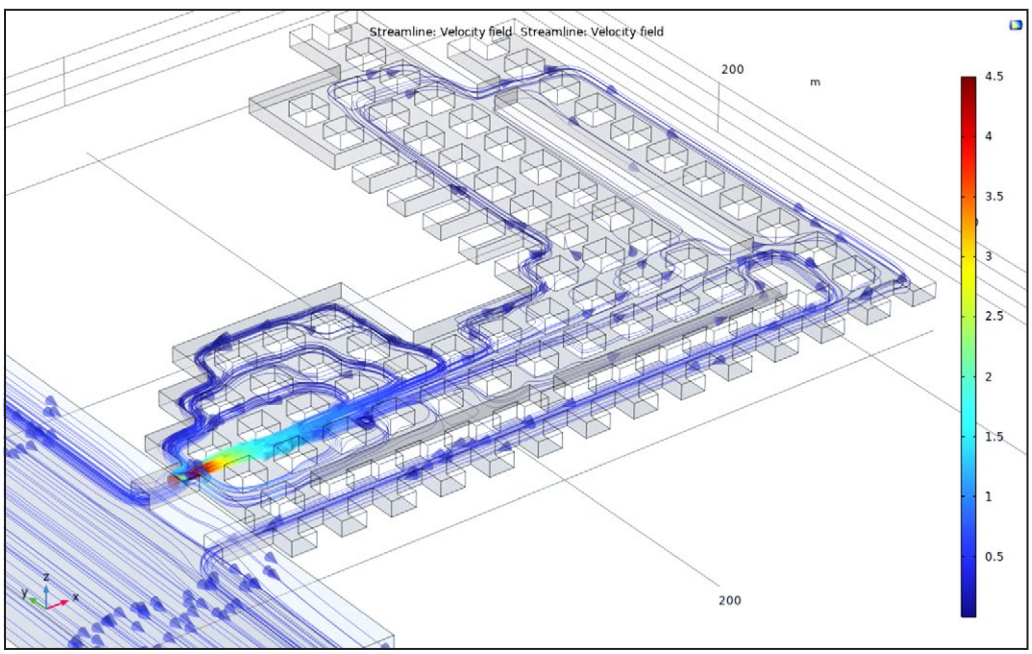

Figure 7. Velocity streamlines of the model with the main fan

airflow quantity. In the following section, modeling of the movement of a truck and how it affects the airflow in the mine are simulated. As stated before, it was also suggested in research done by NIOSH in early 2000 that movement of a truck in the mine can affect the airflow in the mine [4, 7, 8].

Scenario 3: Modeling with Truck Movement in the Mine Without a Fan

The haul trucks entering and leaving the large-opening mines does impact the airflow movement in the mine [7]. In order to show the simulation of the movement of the truck in the mine, we first looked at the movement of a

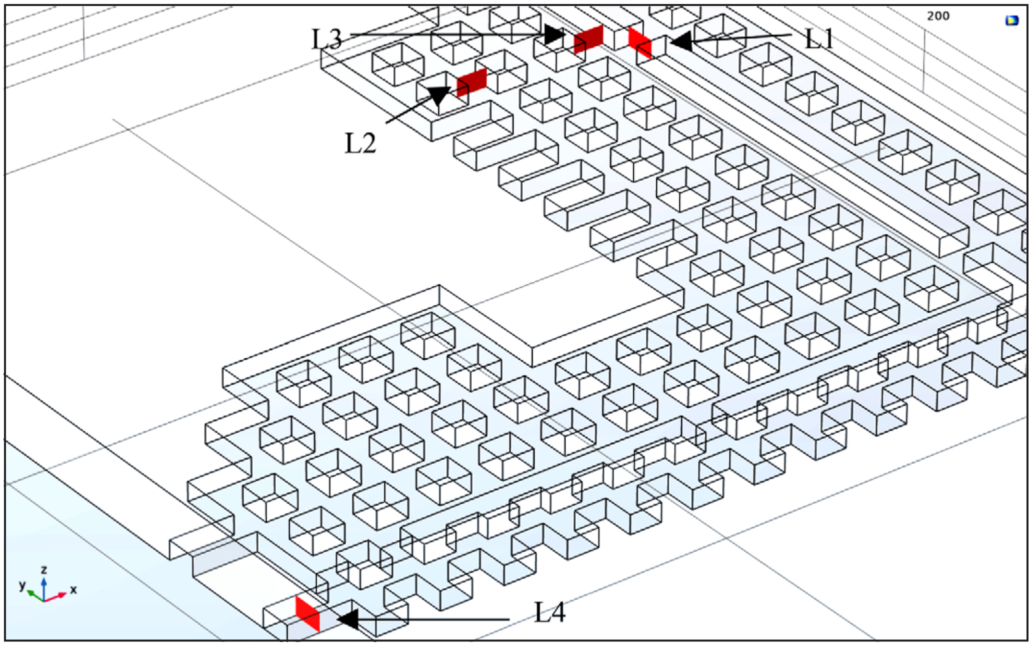

Figure 8. Sampling locations for comparing airflow quantity

Table 1. Comparison of the airflow at different locations (numbers shown are in m^3/s and cfm within parentheses)

	Base Case	3.66-m diameter fan	3.66-m and 2.44-m diameter fans	3.66-m and 0.91-m diameter fans
Location 1	0.087 (184)	21.250 (45,026)	17.426 (36,923)	30.334 (64,274)
Location 2	0.009 (919)	4.301 (9,113)	18.096 (38,343)	3.950 (8,369)
Location 3	0.068 (144)	6.085 (12,893)	57.543 (121,926)	10.472 (22,188)
Location 4	3.055 (6473)	56.181 (119,040)	51.950 (110,075)	51.035 (108,137)

truck going in and coming out of the mine without any fan in the model domain. This was done to assess the impact of just the movement of a truck on airflow inside the mine. Later, a fan was added to the return side of the mine as placing the fan at the entry did not provide space to create a moving domain to model the movement of a truck. Figure 9 shows the placement of the truck in the model domain near the entry. Modeling of the moving object in COMSOL Multiphysics has been discussed in detail by the authors' previous work [18]. However, in the current work, the modeling is in three-dimension and the truck height was at 3.9 m (13 ft) which is 3 m (10 ft) above surface level. A moving domain for the truck movement was created, which is 457-m (1,500-ft) long, 9-m (30-ft) wide and 6-m (20-ft) high. This dimension allowed the truck to move in and out of the mine to the Return 1.

Modeling a moving body in CFD is challenging as the model needs to solve for both airflow and movement of the body in the fluid domain. Apart from that, the most critical aspect is the meshing of the moving domain as well as the rest of the geometry. Figure 10 shows the mesh elements of the moving domain and around the truck body. As from shown in Figure 10, it can be seen that mesh around the truck body is tetrahedron and in the moving path there is structured rectangular mesh swept along the moving domain. The mesh elements in the rest of the domain are tetrahedron. The mapped mesh elements are all rectangular block in a shape which is advantageous for moving body simulation. As the moving body changes position, the mesh element expands and contracts which usually changes the mesh quality, but in the case of mapped mesh, their mesh quality does not change due to its shape.

The speed of the truck in the simulation was assumed to be 9 m/s, which is 20 miles per hour. The model was run for 45 seconds for both cases when the truck is going in and coming out of the mine. The velocity streamline of the simulation result at 20 seconds of the truck moving in the mine is shown in Figure 11. It can be seen from the figure

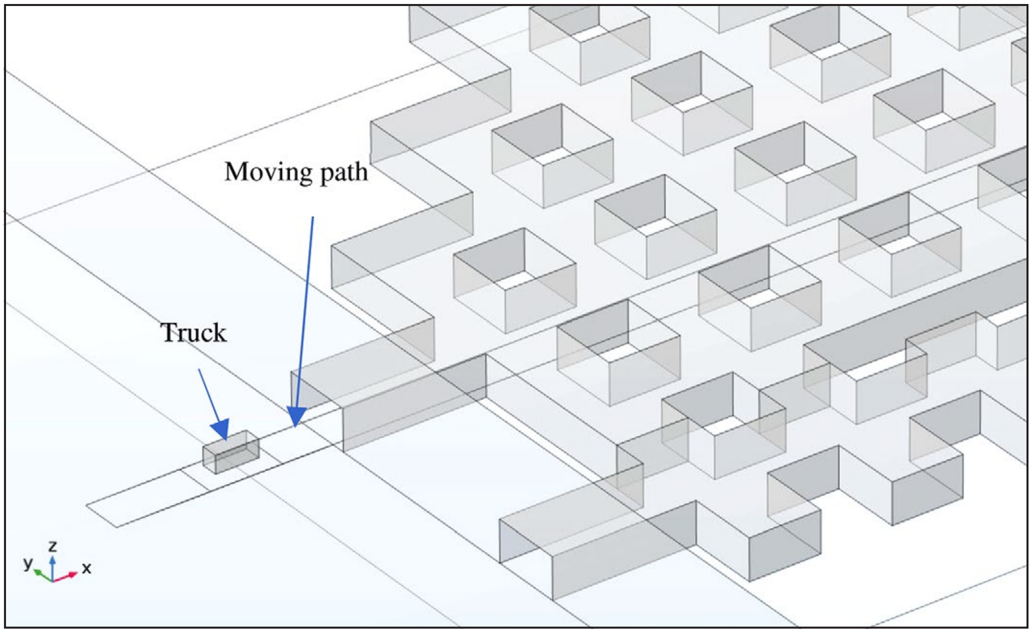

Figure 9. An expanded view of the truck in the model

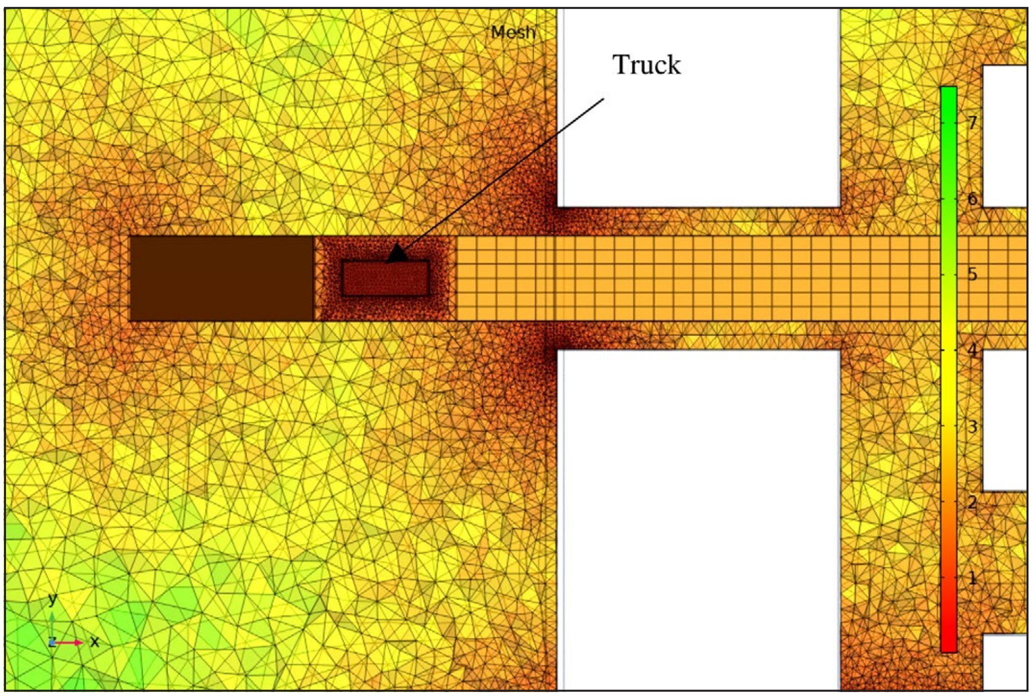

Figure 10. An expanded view of the mesh elements around the truck body and moving domain

that movement of the truck does change the airflow pattern inside the mine. In order to compare both cases, airflow through different sampling locations as shown in Figure 8 were plotted for the simulation time.

Figure 12 presents the airflow quantity at different sampling locations for simulation time. It can be seen from the figure that there is a positive impact on the airflow at different sampling locations with the movement of a truck. This is more evident at Location 4 which is the main return of the mine, where airflow increased from 30 m^3/s (63,500 cfm) to 60 m^3/s (127,100 cfm) when a truck is going in and 30 m^3/s (63,500 cfm) to 45 m^3/s (95,350 cfm) while a truck coming out of the mine. However, not much increase was noticed at the sampling locations inside the

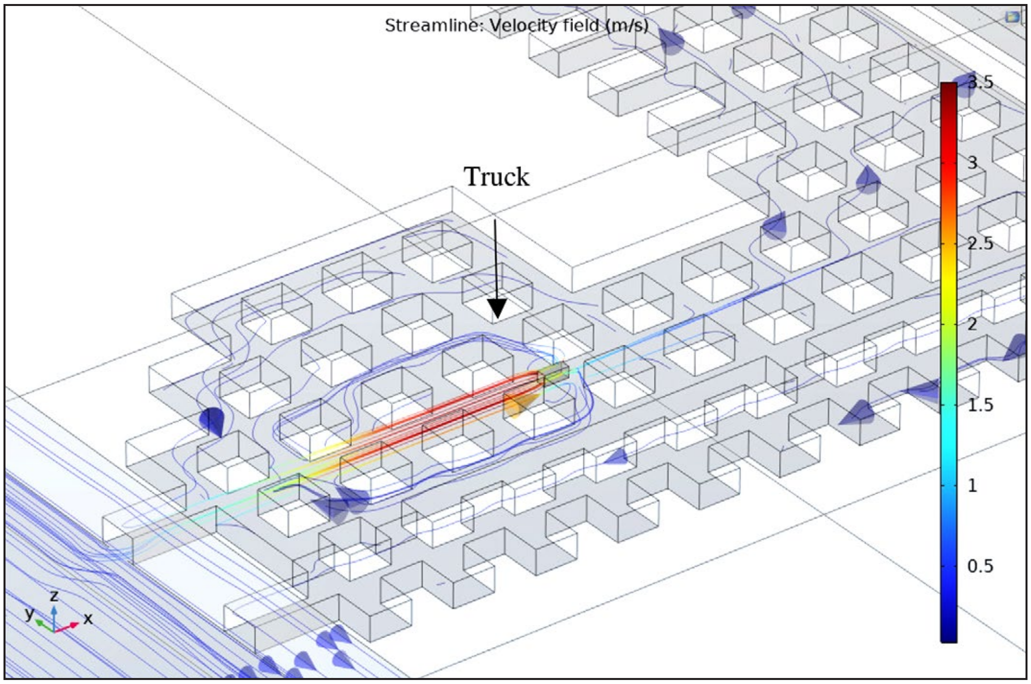

Figure 11. Velocity streamlines of the model with a truck at t = 20 seconds

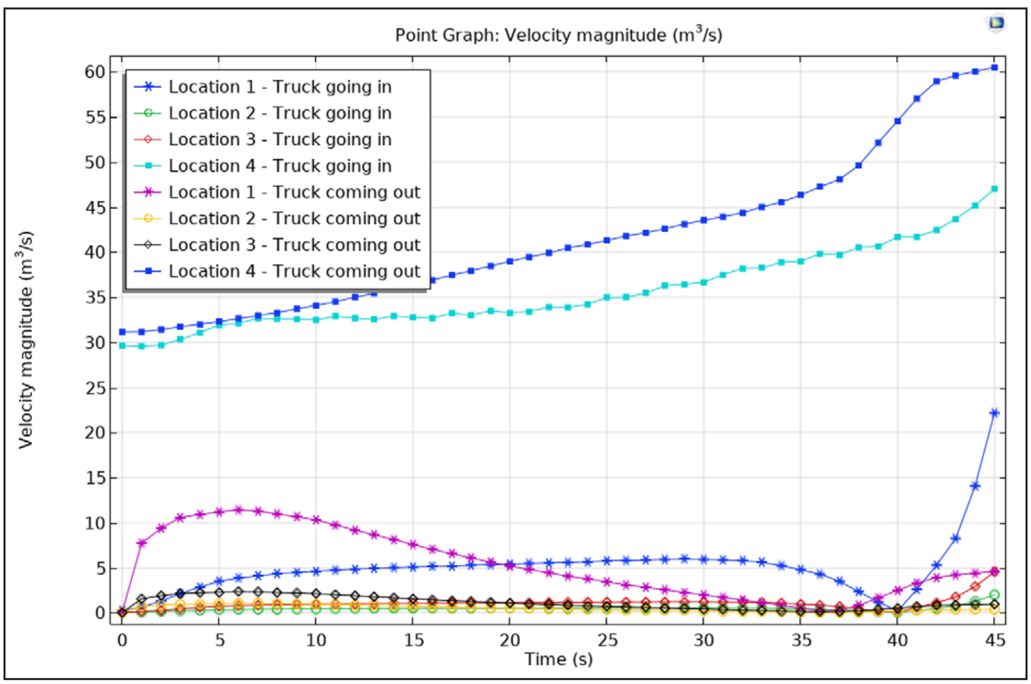

Figure 12. Airflow through different sampling locations with truck movement without a fan

mine, but Location 1 saw the most increase in both cases. The airflow quantity increase at Location 1 was from zero to around 22 m^3/s (46,600 cfm) when the truck was going in the mine, and while coming out of the mine the maximum airflow reached was around 11 m^3/s (23,300 cfm).

Scenario 4: Modeling with Truck Movement in the Mine with Fan

In this scenario, a combination of the above two scenarios were modeled: the truck's movement and a 3.66- m diameter fan running near the Main Return (Figure 13). Again, modeling was done considering the truck movement going in and coming out of the mine. The mesh configurations were similar to the last scenario. Figure 14 shows the expanded view of the mesh. The movement of the truck was simulated for 45 seconds for the truck going in and coming out. The velocity streamline of the simulation result at 20 seconds of the truck moving in the mine is shown in Figure 15. Similar to the previous scenario, results were compared by taking the airflow quantity at different cross-sections as shown in Figure 8.

Both models were compared to see the change in the airflow due to the movement of a truck going in and

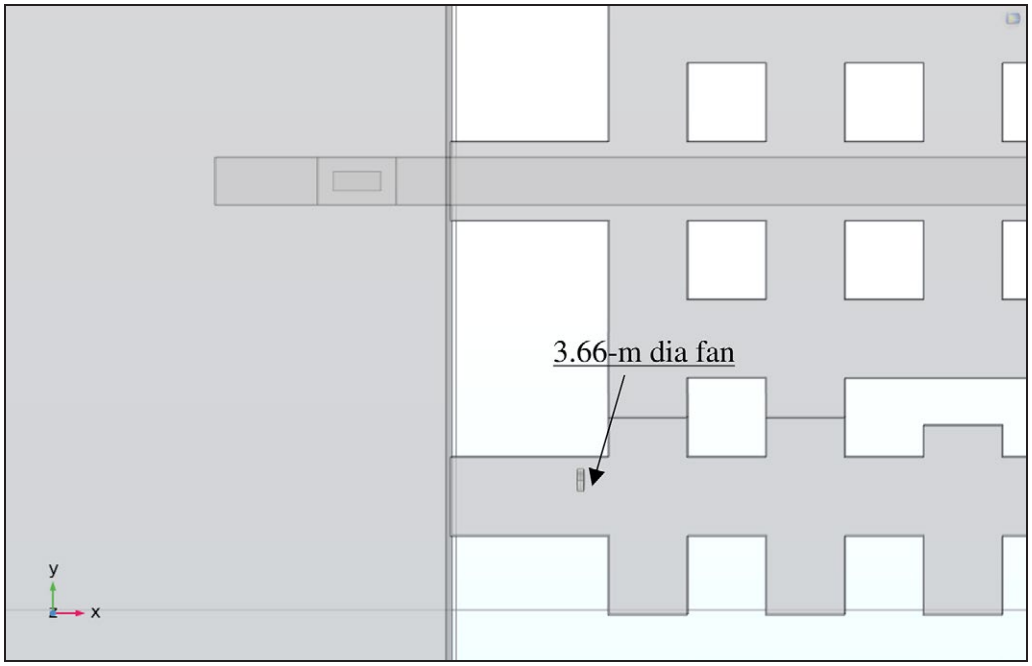

Figure 13. A fan located near the Main Return with a truck going into the mine

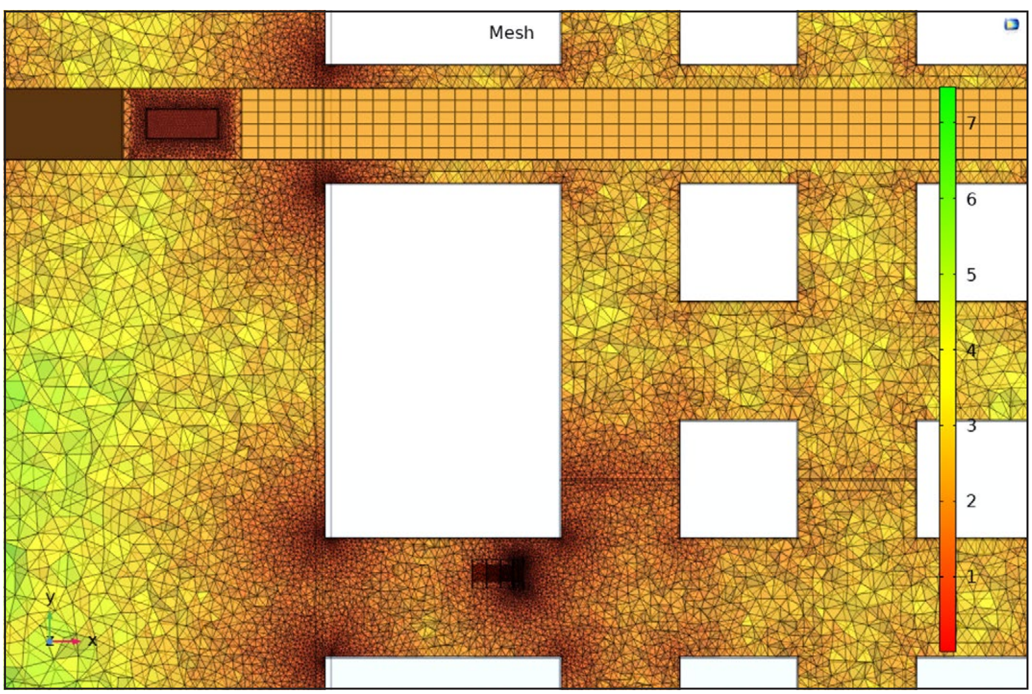

Figure 14. An expanded view of the mesh elements around the truck body and moving domain

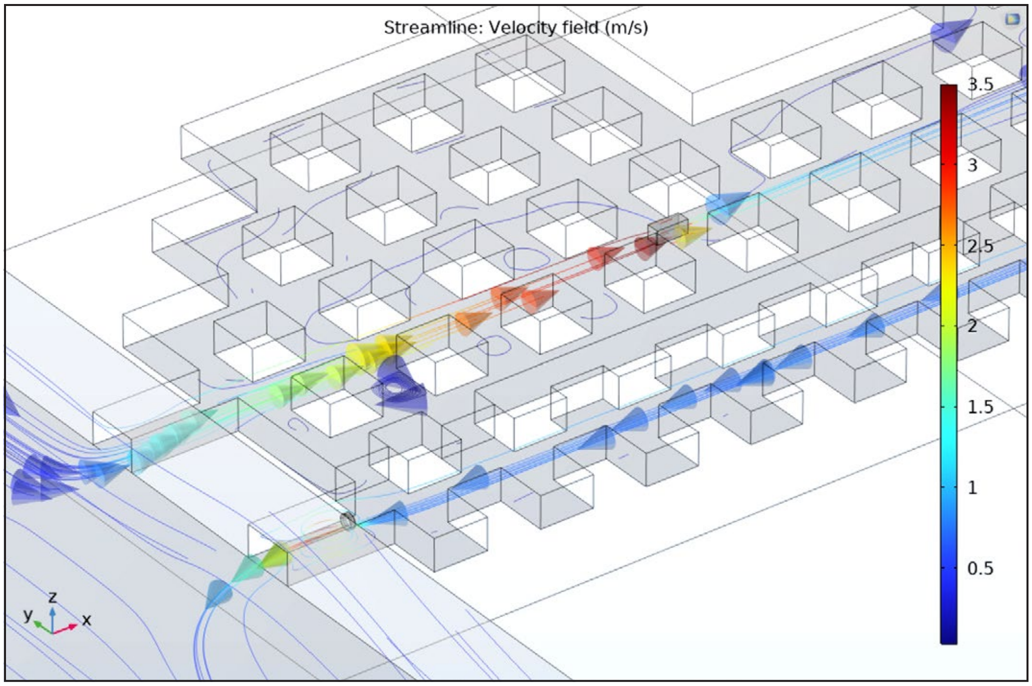

Figure 15. Velocity streamlines of the model with the truck at t = 20 seconds

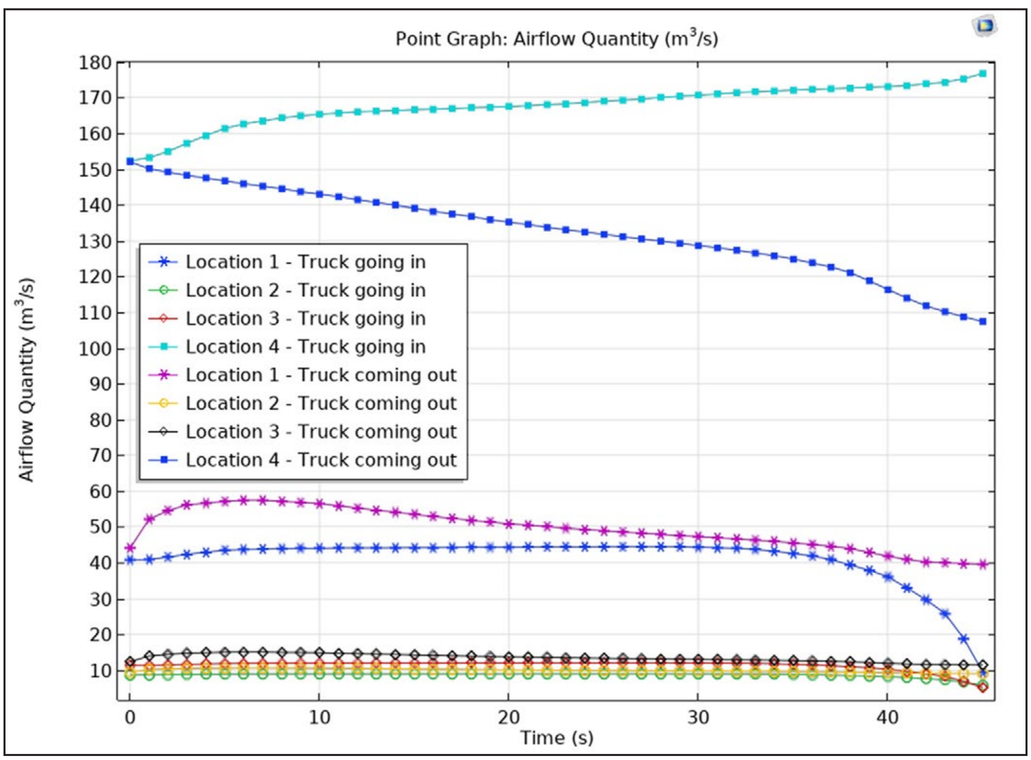

Figure 16. Average air velocity through different sampling locations with truck movement

coming out of the mine. Figure 16 presents the airflow quantity at different sampling locations for simulation time. Simulation results show that the airflow pattern at different sampling locations is impacted by truck movement. When the truck is going in the mine, it pushes the air while entering the mine leading to higher airflow at the Main Return (Location 4). The truck is working against the flow of air from the fan when the truck is coming out of the mine which leads to a decrease in airflow. The airflow quantity at the Main Return is around 150 m^3/s (317,000 cfm), and it went up to around 180 m^3/s (381,000 cfm) in the case of the truck going into the mine. The airflow quantity went down to around 110 m^3/s (233,000 cfm). This change in the airflow was not much observed at other locations. At the Return 2 (Location 1), there was a slight increase in the airflow quantity followed by its decrease.

SUMMARY

The ventilation of large-opening underground stone mines has not been explored much, and it is challenging due to the larger dimension of the mines. Research in the past has suggested that having proper fan placement and movement of a truck in the mine can help the ventilation of large-opening mines. NIOSH investigators considered different scenarios to model such as fan placement in the mine, movement of a truck, and a combination of fan and truck movement in the mine. The CFD modeling results presented in this paper show that placement of a fan can both positively and negatively impact the ventilation of fresh air at different locations in the mine. Simulation results from the movement of a truck with no fan showed that a truck going in the mine can lead to more airflow at the return side but may not be able to ventilate other areas. A fan and truck combination did show changes in the airflow at the Main Return but did not have much impact on the airflow at other locations in the mine. Extending the model domain beyond the mine opening did help in achieving better modeling results in understanding the airflow with fan and movement of a truck.

This study does demonstrate that CFD as tool can be used to understand airflow in a large opening mine and has potential to utilize complex airflow model such as movement of body in fluid domain and play a part in decision making for mine operators in terms of fan placement and utilization of moving equipment operating in the mine to improve ventilation.

LIMITATION OF THE STUDY

The current simulation study was based on the work done in the past by NIOSH researchers and does offer some insight on the impact of truck movement on airflow pattern inside a large opening mine, however, the findings of this work is limited to the movement of truck going in and coming out of the mine. At the same time the results of the simulation were not validated using data collected from any current working mine and cannot be implemented to a wide range of mining conditions. There are also factors such as mine layout, release of DPM from trucks and other equipment, influence of external and internal environment, fan size, placement of fans among other not considered in this study.

DISCLAIMER

The findings and conclusions in this report are those of the author(s) and do not necessarily represent the official position of the National Institute for Occupational Safety and Health (NIOSH), Centers for Disease Control and Prevention (CDC). Mention of any company or product does not constitute endorsement by NIOSH.

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