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CFD ANALYSIS ON GAS DISTRIBUTION FOR DIFFERENT SCRUBBER REDIRECTION CONFIGURATIONS IN SLAB CUT AND SUMMARY OF PREVIOUS SUMP CUT ANALYSIS

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ABSTRACT

The National Institute for Occupational Safety and Health (NIOSH), Pittsburgh Mining Research Division (PMRD) has recently developed a series of models utilizing computational fluid dynamics (CFD) to study gas distribution around a continuous mining machine (CM) with various fan-powered flooded bed scrubber discharge configurations in an exhaust curtain working face. CFD models utilizing species transport model without reactions in FLUENT were constructed to evaluate the redirection of scrubber discharge toward the mining face rather than behind the return curtain. The study illustrates the gas distribution in the slab (second) cut. The following scenarios are considered in this study: 100% of the discharge redirected back towards the face on the off-curtain side of the continuous miner; 100% of the discharge redirected back towards the face, but divided equally to both sides of the machine; and 15% of the discharge redirected toward the face on the off-curtain side of the machine, with 85% directed into the return. These models were compared to a model with a conventional scrubber discharge where air is directed away from the face into the return. The models were validated based on experimental data and accurately predicted sulfur hexafluoride (SF_6) gas levels at four gas monitoring locations. One additional prediction model was simulated to consider a different scrubber discharge angle for the 100% redirected, equally divided case. This paper describes the validation of the models based on experimental data and the gas distribution results of the CFD models.

INTRODUCTION

To control methane gas and dust concentrations on continuous mining operations, it is important to provide sufficient quantity of fresh air from the end of tubing or curtain to the active face. In this region, operating machine-mounted water sprays and fan-powered, flooded bed scrubbers can significantly increase the amount of airflow reaching the face [1-3].

However, when an entry is large, especially in higher coal seams, the water spray configuration and the scrubber capacity may not be adequate to maintain sufficient forward airflow to confine the dust cloud to the face. Dust can roll back toward the machine operator as a result [4]. Currently, several coal mines having negligible gas emissions in higher coal seams (2.4 to 3.0 m [8 to 10ft.] thick) with exhaust tubing systems redirect the scrubber discharge back towards the face in an effort to improve dust collection. NIOSH studied the redirected scrubber exhaust techniques for dust and gas control in a full scale CM gallery to assess its potential for industry-wide application [5].

For a CM face, previous studies have concluded that the behavior of gas and respirable dust is a complex process. The distribution/dispersion and transport of gas and respirable dust after they are liberated at the face are governed mainly by their mass properties, the movement pattern of the ventilation air, and interactions with the mining machine and water droplets created by the external water spray systems used for dust control [6-10]. To understand these behaviors in a complex CM environment and to evaluate the effectiveness of various control techniques, numerical modeling has become a necessary supplement to laboratory experiments and field studies.

Early computational recirculation studies have focused on general-body concentrations and assumed that methane and air are completely mixed at regional areas in the mine [11-12]. Some studies also examined localized recirculation devices (fans, compressed-air injectors, sprays, etc.) to increase air velocities and induce air mixing to reduce gas stratification [13]. Due to the limitation of the tools, they do not necessarily provide insights into the gas mixing and concentration gradients at the mining face.

To provide the detailed distribution information instead of the general mixture supposed above, CFD simulation can be an effective tool for that purpose. In mining research, CFD has been used to detect spontaneous combustion and apply inertization in gob areas [14-15], investigate longwall dust control [16], study airflow and gas distribution in common CM ventilation configurations [17-21], visualize diesel emissions dissipation in underground metal/nonmetal mines [22], and estimate a mine's ventilation status after a disaster [23]. CFD modeling has become a powerful tool for understanding airflow movement and gas/dust behavior in a complicated three-dimensional environment.

The objective of this study is to use CFD techniques to build a numerical model of PMRD's CM test gallery and validate the model from experimental findings from prior PMRD laboratory research. Previously, experimental and simulated studies of gas distributions in the face area of a sump cut were conducted. Figure 1 illustrates the full-scale miner at the sump cut position with a 1.2 m [3.9 ft.] wide by 6.1 m [20 ft.] long block of coal in the slab portion of the cut. The CM was equipped with an on-board scrubber operated at a flow rate of 3.3 m^3/s [7,000 cfm] through the modified discharge ducts.

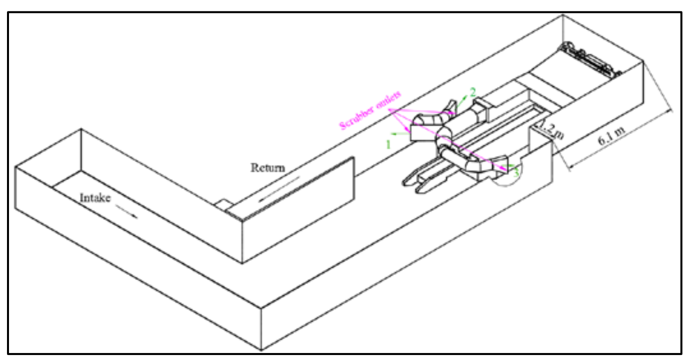


Figure 1. Layout of the Full-scale CM Gallery for Scrubber Redirection Experiments in Sump Cut.

For that study, the scrubber exhaust discharge configurations examined were: 1) Conventional, 100% of the air directed outby on the curtain side of the face from scrubber exhaust location 1; 2) 85/15, 15% of the air redirected to the off-curtain side of the mining machine from exhaust location 3, and 85% of the air directed outby on curtain side of the face from exhaust location 1; 3) 50/50, 100% of the discharge redirected back towards the face, divided equally from exhaust location 2 and 3; and 4) 100% R, 100% of the air directed toward the face on the off-curtain side of the mining machine from exhaust location 3.

Due to the block of coal in the slab portion of the cut in the sump cut study, it was found that the off-curtain corner can have about 10 times higher gas concentrations as compared to the curtain corner for the conventional case. The off-curtain corner was only slightly improved in the 85/15 case, although high concentrations of gas were detected above the top of the cutting drum. For the 50/50 and 100% R cases, the reuse of the scrubber exhaust flow did lower the peak gas concentration at the corners of the CM face, but increased gas concentrations around the continuous mining machine [24].

This study reveals the same scrubber discharge cases as the sump cut with the miner positioned in the slab cut of the continuous mining CM face and without the effect of the block of coal at the off-curtain side of the machine. As in the sump cut study, four experimental cases and one prediction case were evaluated. By combining the results from the sump cut and the slab cut, the whole picture of the airflow pattern and gas distribution for conventional scrubber and scrubber redirection usage is revealed and can be used to identify the factors affecting airflow distribution in the face area.

METHODS

Laboratory Experiments

The detailed layout of this full-scale CM facility is shown in Figure 2 with an exhaust ventilation curtain extended to within 12.2 m [40 ft.] of the mining face [25]. A 12.2 m [40 ft.] distance represents the largest curtain setback typically encountered while mining extended (deep) cuts [26]. The dimensions of the gallery entry are 5.5 m [18 ft.] wide by 2.1 m [7 ft.] high, with a full-scale mockup of a Joy CM14 continuous mining machine positioned at a simulated mining face. In this study, the machine was located at the end of the 40-ft slab cut as shown in Figure 2. Face airflow was measured by moving traverse at the inlet of the exhaust curtain (0.91 m [3 ft.] width) with a vane anemometer at the beginning and end of each experimental run to verify a flow rate of 5.66 m^3/s [12,000 cfm].

The full-scale miner was equipped with an on-board scrubber with modified discharge ducts as shown in Figure 2. The scrubber was operated at a flow rate of 3.3 m^3/s [7,000 cfm] for various scrubber configurations through the three scrubber openings under cutter boom (View 2 in Figure 2). The scrubber discharge configurations examined were shown in Table 1.

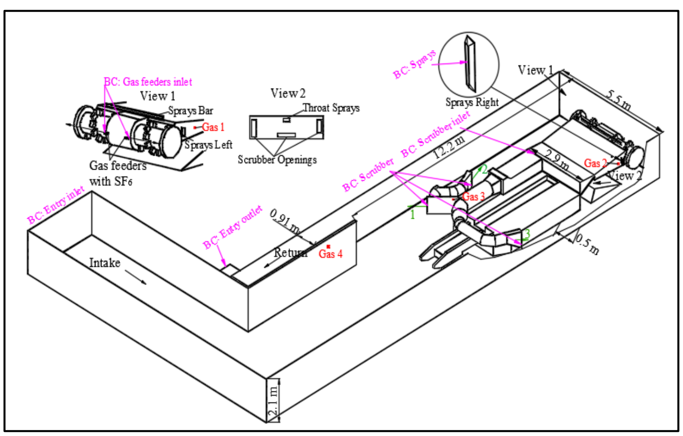


Figure 2. Layout and Dimension of the Full-scale CM Gallery for Scrubber Redirection Experiments in Slab Cut. Locations of Boundary Conditions (BC) are also shown in the Figure.

External sprays consisted of fifteen top-mounted boom sprays (Sprays Bar in View 1 of Figure 2) directed at the top of the rotating drum, three under boom throat sprays (View 2 of Figure 2) directed at the loading pan, and three sprays on each side of the cutter boom directed at the drum's end rings (Figure 2 and View 1 of Figure 2). Groups of sprays were combined and modeled as truncated rectangular pyramids with a base angle of 41 degrees, as indicated by the detailed view of sprays on the right.

Table 1. Simulation Cases with Different Scrubber Redirect Configurations in Slab Cut.

Study cases	Description
1) Conventional	100% airflow discharged from scrubber discharge outlet 1
2) 85/15	85% airflow discharged from scrubber discharge outlet 1 and the other 15% from scrubber discharge outlet 3
3) 50/50_23D	50% airflow discharged from scrubber discharge outlet 2 and the other 50% airflow from scrubber discharge outlet 3, the discharge angle was 23° from the body
4) 100% R	100% airflow discharged from scrubber discharge outlet 3
5) 50/50_45D	50% airflow discharged from scrubber discharge outlet 2 and the other 50% airflow from scrubber discharge outlet 3, the discharge angle was 45° from the body

Sulfur hexafluoride (SF_6) gas was introduced in front of the rotating cutting drum at a constant dose rate from two tubes on the left and right side (View 1 of Figure 2). SF_6 gas measurements were continuously sampled and recorded at the curtain and off-curtain side of the cutter boom (Gas 1 and Gas 2 as shown in Figure 2 and View 1 of Figure 2). Also, gas measurements were recorded inside the scrubber duct close to the duct junction (Gas 3 in Figure 2) and in the return air course (Gas 4 in Figure 2).

CFD Modeling

CFD simulations were conducted with ANSYS FLUENT 15.0 (ANSYS Inc, Canonsburg, PA). Species transport model without reactions was used to study the gas distribution in the mining face area. Five simulation cases were considered in this paper with steady-state analysis, four of which were based on the laboratory experiment settings; the fifth was based on using modified scrubber discharge angles. All the cases are illustrated in Table 1.

This study represents the slab (second) cut of the CM face. The locations of the boundary conditions are illustrated in Figure 2. Fresh air entering the face is illustrated by an entry inlet with a fixed air velocity to provide face ventilation. An outlet with zero gauge pressure was placed behind the exhaust return curtain. The scrubber's airflow was controlled at four locations according to the different simulation scenarios. At the scrubber inlet, a fan condition was assigned to draw air into the system. In order to model each case, a wall, or an interior plane, or a fan was placed at each of the three scrubber outlets to provide the airflow according to the experimental configurations. To model the air-moving effects of the machine-mounted water sprays, a fan condition was placed at the four spray locations, representing the nozzle-induced airflows. For the SF_6 gas feeders, a velocity inlet was created with a fixed velocity and fixed mass fraction of gas. All the other boundaries within the domain were defined as interior planes or walls. The meaning and location of different boundary conditions are the same obtained from the calibration process in sump cut study [24]. Table 2 summarizes the inputs for this slab cut simulation.

Table 2. Input Parameters for CFD Models in Slab Cut.

Simulation setups	Parameter descriptions
Simulation model	Species transport model without reactions
Turbulence model	k-ε, realizable, enhanced wall condition
Boundary conditions	Entry inlet: velocity inlet (0.98 m/s [193 fpm])
	Entry outlet: pressure outlet (0 Pa)
	Sprays: fan (40 Pa)
	Scrubber: fan/wall/interior plane (depend on the case and location)
	Gas feeders: velocity inlet (3.86 m/s [760 fpm]), mass fraction of gas 0.0056
	Others: wall or interior plane
Solution method	Pressure-velocity coupling scheme: SIMPLE
	Spatial discretization for gradient: Green-Gauss Node Based; for pressure: PRESTO; others: 2^{nd} order upwind

RESULTS AND DISCUSSION

Comparison of CFD Modeling to Laboratory Experiments

Table 3 shows that the CFD simulation cases agreed well with the experimental data (with differences of less than ±15%) at the four gas monitoring locations. Because of the agreement of simulations with experimental data, the simulation results can be used with reasonable accuracy to investigate gas distributions in the CM gallery.

Table 3. Percent Difference (Diff.) between Experiment (Exp.) and CFD Simulation (CFD) in Slab Cut.

Experiment cases		*Gas 1	Gas 2	Gas 3	Gas 4
Conventional	Exp. (SF_6 ppm)	0.78	6.43	2.93	1.52
	CFD (SF_6 ppm)	0.73	6.37	2.79	1.44
	Diff. (%)	-6.41	-0.93	-4.78	-5.26
85/15	Exp. (SF_6 ppm)	2.14	0.86	3.29	1.53
	CFD (SF_6 ppm)	2.10	0.89	3.20	1.40
	Diff. (%)	-1.87	3.49	-2.74	-8.50
50/50_23D	Exp. (SF_6 ppm)	7.06	4.91	6.81	1.37
	CFD (SF_6 ppm)	6.31	4.54	6.99	1.23
	Diff. (%)	-10.62	-7.54	2.64	-10.22
100% R	Exp. (SF_6 ppm)	3.13	1.68	2.26	1.61
	CFD (SF_6 ppm)	2.69	1.75	2.48	1.85
	Diff. (%)	-14.06	4.17	9.73	14.91

* Gas 1, 2, 3, and 4 are the four SF_6 monitors, located as shown in Figure 2.

Case Study 1) Conventional, 100% discharge. In the conventional case, 100% of scrubber discharge airflow came from scrubber outlet 1 (Figure 2), which is the normal discharge pattern of the scrubber. The airflow pattern shown in Figure 3 revealed that as the ventilating air flowed toward the face, some of the airflow went directly to the return, while a portion was drawn toward the three scrubber openings. Of the 3.3 m^3/s [7,000 cfm] scrubber flow rate capacity, about 1.3 m^3/s [2,800 cfm], 1.2 m^3/s [2,500 cfm], and 0.8 m^3/s [1,700 cfm] were divided between the left, middle, and right scrubber openings, respectively. As a result, it can be observed from Figure 3 that most of the air that flowed toward the face went to the left side (curtain side) of the entry. The higher flow rate through the left and middle scrubber openings can be attributed to the location of the scrubber on the left side of the continuous mining machine and closer to the two openings. These scrubber opening flow rates were consistent for all the other simulation cases studied.

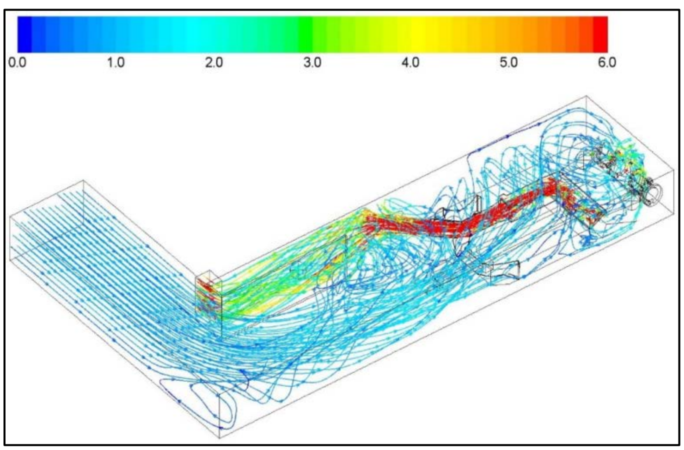


Figure 3. Pathline of Fresh Airflow (conventional) in Slab Cut, Different Colored Arrow Lines Representing the Velocity (0.0-6.0 m/s) of Different Particles Released from Entry Inlet.

On the right corner of the CM face, there was a recirculation of air introduced by the sprays on top of the CM, which was high on gas concentrations. As some of the fresh airflow moving toward the face from the right top and side of machine, they met with the above recirculation airflow and continuously dilute this high gas region. However, as the fresh airflow was not strong enough, it cannot penetrate the recirculation and ventilate the right corner.

This airflow pattern reduced the gas level on the left side of the face area (0.78 ppm from the experiment, 0.73 ppm from CFD) as shown in Figure 4. The gas accumulation was about eight times higher on the right side of the face area (off-curtain side, 6.43 ppm experiment, and 6.37 ppm CFD).

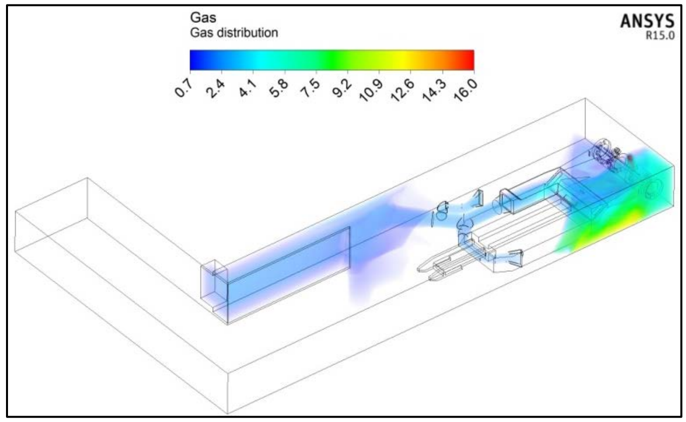


Figure 4. Gas Concentrations for Simulation of Conventional Scrubber Discharge in Slab Cut, Gas Level: 0.7 - 16.0 ppm.

As shown in Figure 4, a portion of the gas stream missed the scrubber opening on the off-curtain side and was pushed backward. This is mainly caused by the airflow induced from the top-mounted boom sprays. Also, the air and gas mixture discharged from scrubber outlet 1 impacted the wall close to the curtain creating turbulence in that area.

Case Study 2) 85/15, 85% conventional discharge with 15% scrubber redirection. In the 85/15 case, 85% of airflow (2.83 m^3/s [6,000 cfm]) was discharged from scrubber outlet 1 and the other 15% (0.47 m^3/s [1,000 cfm]) from scrubber outlet 3 (off-curtain side). Compared to the conventional scrubber flow, the 85/15 configuration induced more airflow to the off-curtain side of the face area as shown in Figure 5. This forward airflow was powerful enough to penetrate the recirculated airflow at the off-curtain corner of the entry that was evident in the conventional case simulation. The airflow from scrubber outlet 3 was mainly discharged at the ground level and combined with airflow that was induced at a higher level, moved the air toward the left side (curtain side) of the face. Also, a weak circulation area at the left corner of the face was present as shown in Figure 5 by mostly fresh ventilation airflow.

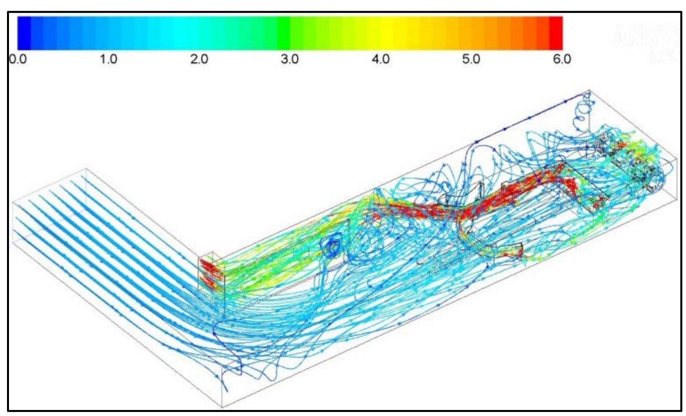


Figure 5. Pathline of Fresh Airflow (85/15) in Slab Cut, Different Colored Arrow Lines Representing the Velocity (0.0-6.0 m/s) of Different Particles Released from Entry Inlet.

The airflow from right to left side of the face reduced gas concentration near the front right corner of the machine (off-curtain side) when compared to the the convention simulation results as shown in Figure 6. At the same time, the gas migrated to the left side of the machine and increased the gas concentrations at gas sampling location 1.

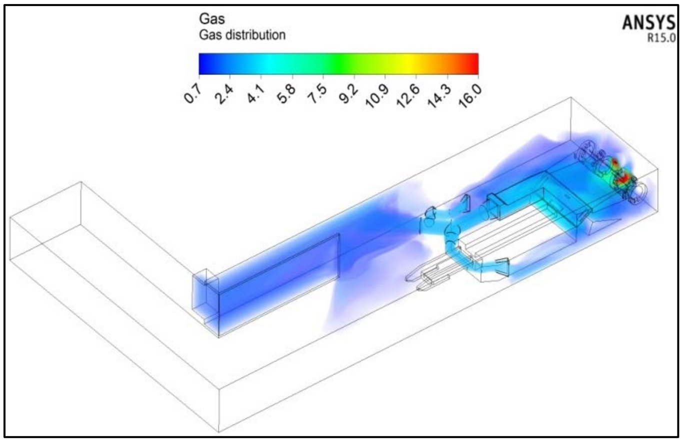


Figure 6. Gas Concentrations for Simulation of 15% Scrubber Redirection and 85% Conventional Scrubber Discharge in Slab Cut, Gas Level from 0.7 to 16.0 ppm

Results from the 85/15 sump cut case study [24] showed high gas levels formed in the face region above the cutting drum. The 85/15 slab cut case did not show that serious high gas plume hanging above the cutting place due to the higher airflow sweeping the face from the right side of the CM machine, which effectively reduced recirculation above the cutting drum as shown in Figure 6.

Case Study 3) 50/50_23D, 50% redirection to curtain side and 50% to off-curtain side. In this case study, 100% scrubber discharge was redirection toward the face, 50% of airflow was discharged from scrubber outlet 2, and 50% from scrubber outlet 3. The discharge angles of both outlets were approximately 23 degrees away from the body of the CM.

The outlet area was 0.093 m^2 [1 $ft.^2$] for both the left and right scrubber outlets, with an average airflow speed of 17.78 m/s [3,500 fpm] at the outlet opening. This configuration created a large area of turbulence in the front of the CM. As shown in Figure 7, the airflow traveled down the ribs on the left and right side of the CM machine across the face and created a turbulent area at the left side of the cutting drum.

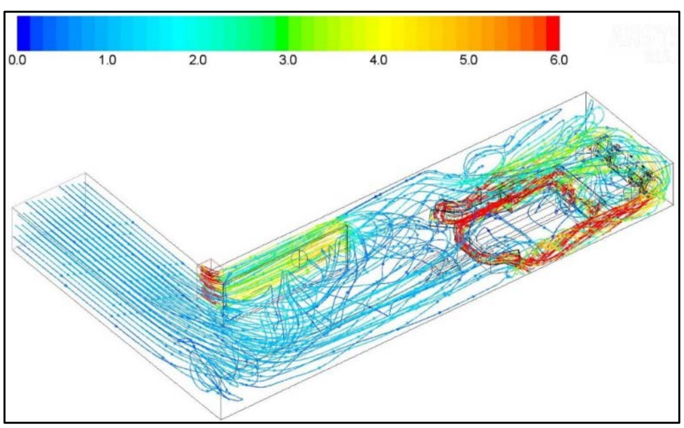


Figure 7. Pathline of Fresh Airflow (50/50_23D) in Slab Cut, Different Colored Arrow Lines Representing the Velocity (0.0-6.0 m/s) of Different Particles Released from Entry Inlet.

Because the flow of the discharged air created turbulence in the face area, higher and more uniform gas levels are evident in the face region as compared to the previous two simulation cases as shown in Figure 8. The highest gas level was observed on the left side of the cutting drum where the two discharged airflows merged.

Case Study 4) 100% R, 100% redirection to off-curtain side. In this case study, all of the scrubber discharge was from the right outlet (off-curtain side, outlet 3) with a velocity of 35.56 m/s [7,000 fpm].

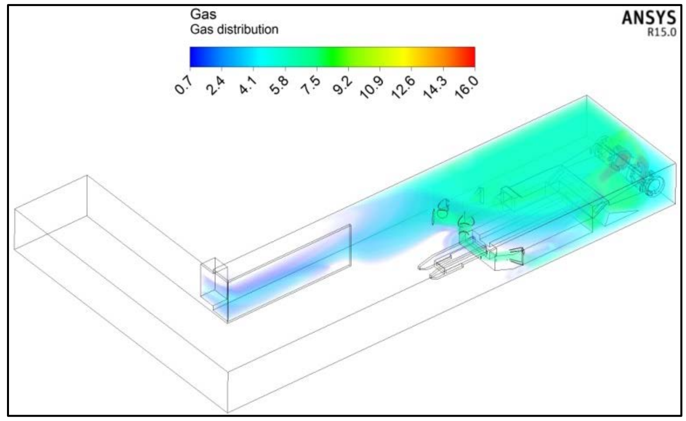


Figure 8. Gas Concentrations for Simulation of Evenly Split 100% Scrubber Redirection in Slab Cut, Gas Level from 0.7 to 16.0 ppm

It can be observed from Figure 9 that airflow from the right scrubber outlet swept down the right side of the entry, across the face area, and then up left side of the entry and traveled behind the curtain. As shown in Figure 10, a portion of the discharged airflow bypassed the inlet to the exhaust curtain and pushed the gas outby the curtain inlet. The airflow pushed the gas to the left side of the entry increasing the gas concentrations in the left corner of the entry.

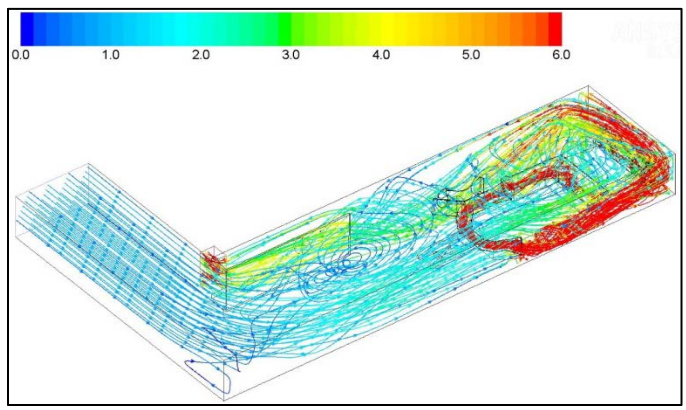


Figure 9. Pathline of Fresh Airflow (100% R) in Slab Cut, Different Colored Arrow Lines Representing the Velocity (0.0-6.0 m/s) of Different Particles Released from Entry Inlet.

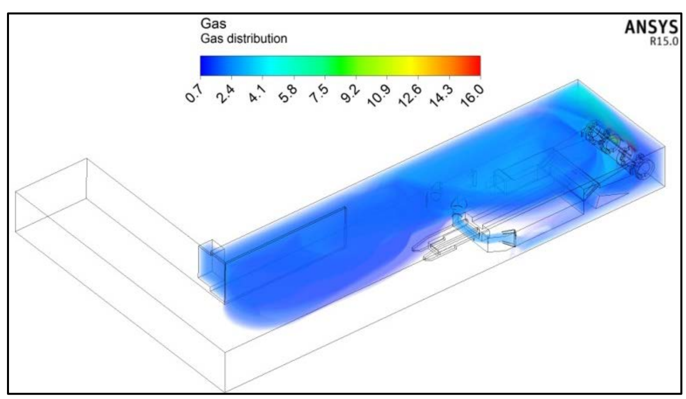
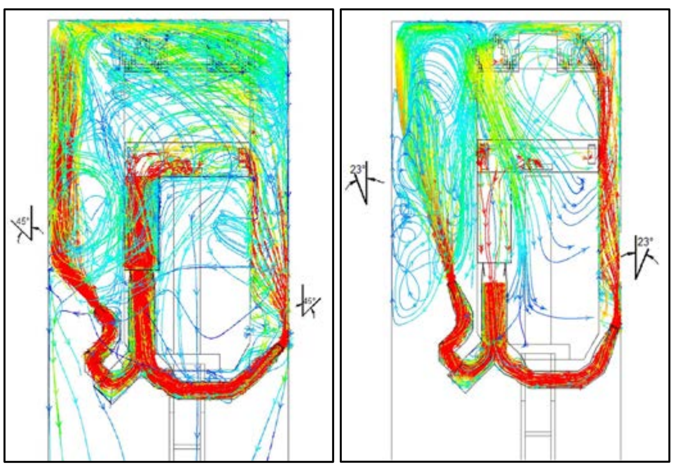


Figure 10. Gas Concentrations for Simulation of 100% Redirected Scrubber Discharge to Off-curtain Side in Slab Cut, Gas Level from 0.7 to 16.0 ppm.

Prediction of Face Conditions Using CFD

After validating the CFD models, it is possible to predict the gas distributions for some interesting simulation cases that may not be practical for laboratory experimentation. For example, NIOSH PMRD researchers have observed an underground U.S. mine with 3.0 m [10 ft.] height redirecting 100% of the scrubber discharge toward the face from both sides of the CM. This configuration was similar to the 50/50 simulation case, but with scrubber discharge angles of 45 degrees from the body of the CM. Though this condition was not evaluated in the previous laboratory experiments, CFD may be used to predict the possible outcome when implemented in a 2.1 m [7 ft.] coal seam face – simulation 50/50_45D. These results can be further compared to those obtained in the prior 50/50_23D simulation with scrubber outlets angled at 23 degrees to identify regions of interest and estimate any possible changes in gas concentrations. For all four previous experimental cases, scrubber outlet 1 is always pointing toward the rib at 45 degrees, and redirected outlets 2 and 3 are all oriented at 23 degrees away from the CM body.

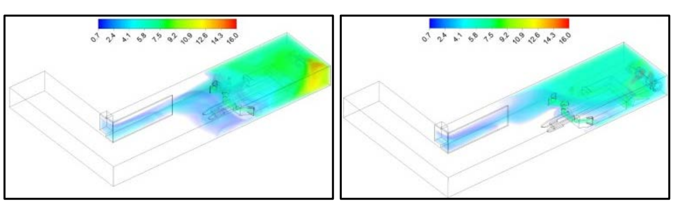
With the scrubber discharge angled at 45 degrees (50/50_45D), airflow from the right scrubber outlet moved away from the right rib and spread across the right side of the CM. A portion of this air flowed toward the three scrubber openings, and also moved toward the face, which dominated the airflow from right to left underneath the cutter boom (Figure 11A). Most of the airflow from the left scrubber outlet flowed close to the left rib and swept the face from left to right. This airflow dominated the ventilation at the face above the cutter boom. As shown in Figure 12A, the airflow from left outlet moved the gas toward the right side of the entry above the cutting drum, a portion of the gas then flowed downward as it reached the right rib and controlled by the flow from the right scrubber outlet afterwards to go underneath the cutter boom.



A) Pathline of airflow (45°) B) Pathline of airflow (23°)

Figure 11. Comparison of Pathline for 45° and 23° Outlets (50/50) in Slab Cut.

The case study with the scrubber discharge angle at 23 degrees (50/50_23D) showed, most of the airflow from the right scrubber outlet traveled toward the face and encountered the airflow from the left scrubber outlet close to the left side of the cutting drum as shown in Fig 11 B. Figure 12 shows the difference in gas concentrations in the entry for both of the simulation cases.



A) Gas level from 0.7 to 16 ppm (45°) B) Gas level from 0.7 to 16 ppm (23°)

Figure 12. Comparison of Gas Concentration for 45° and 23° Outlets (50/50) in Slab Cut.

The gas concentrations for all four sampling locations are listed in Table 4. The simulated gas concentration at left side gas sampling location 1 was predicted to be 48.02 percent higher and at right side gas sampling location 2 was predicted to be 116.52 percent higher when the scrubber discharge was angled at 45 degrees compared to a 23 degree discharge angle.

Table 4. Prediction of Gas Level for 50/50_45D and Comparison with 50/50_23D.

Cases	Gas 1	Gas 2	Gas 3	Gas 4
50 / 50 _45D CFD (SF_6 ppm)	9.34	9.83	7.18	1.22
50 / 50 _23D CFD (SF_6 ppm)	6.31	4.54	6.99	1.23
Diff. (%)	48.02	116.52	2.72	-0.81

DISCUSSION

In this study, the gas distribution around the CM face in the slab cut (second cut) was investigated. Together with the sump cut (first cut) cases from previous research, the comparison of experimental data with simulation results at the four sampling locations are listed in Figs. 13 and 14. It can be observed from the two figures that overall the simulation agreed well with the experimental data (maximum 15% difference).

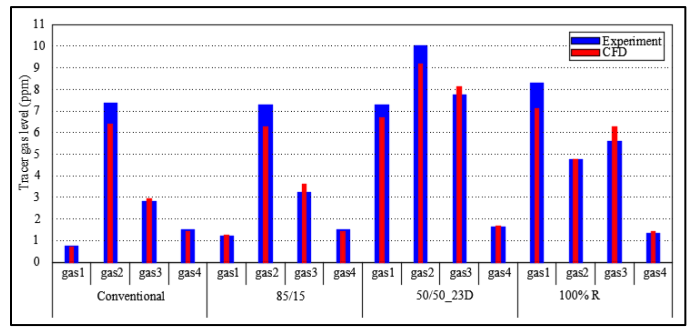


Figure 13. Comparison of Experimental Data with CFD at the Four Sampling Locations (Gas 1-4) in Sump Cut.

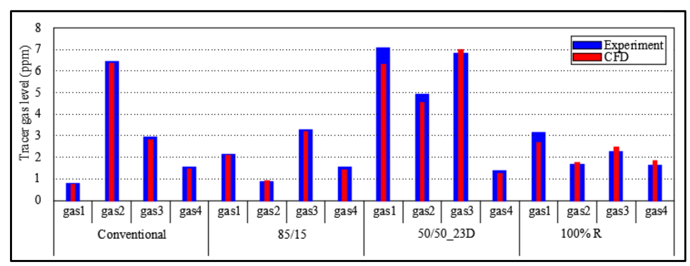


Figure 14. Comparison of Experimental Data with CFD at the Four Sampling Locations (Gas 1-4) in Slab Cut.

For the conventional scrubber ventilation cases in sump cut and slab cut, the gas concentrations are all relatively low except the off-curtain corner (monitor gas 2's location), where the gas levels were considerably higher.

To improve the off-curtain corner, 15% of exhaust airflow (0.47 m^3/s [1000 cfm]) was redirected back toward that corner in the two 85/15 cases. In the sump cut, the off-curtain corner is not improved much when compared to the conventional simulation cases as shown in Figure 13 (gas 2: 7.38 ppm to 7.26 ppm with experimental data and 6.41 ppm to 6.28 ppm in CFD simulation). Also, CFD simulation revealed a phenomenon that was not evident in the experiment data. As shown in Figure 15, there is a potential large and high gas cloud in the right region above the cutting drum. In the slab cut, the off-curtain corner gas levels are much improved.

The two 50/50 cases in sump cut and slab cut, the gas concentrations are all high in both CM corners and within the duct (gas 3), and do not show any improvement when compared to the conventional ventilation cases.

The 100% R case in the sump cut has high gas levels in whole face regions (including gas monitors location gas 1 to 3). In slab cut, the 100% R case swept the face well in the off-curtain corner and has low gas in the duct, although the gas level at the curtain corner is a little higher than the conventional case.

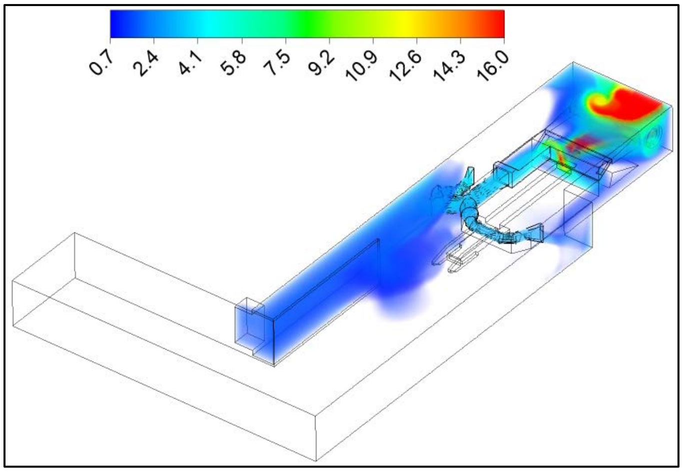


Figure 15. Gas Concentrations for Simulation of 15% Scrubber Redirection and 85% Conventional Scrubber Discharge in Sump Cut, Gas Level from 0.7 to 16.0 ppm [24].

CONCLUSIONS

CFD simulations have proven to be a valuable tool in understanding air and gas flow patterns on a CM face and in studying the effect of various scrubber redirection configurations on gas distribution and on detecting potential high gas level regions.

In this slab cut study, it can be observed that the conventional scrubber ventilation provide most of the face regions clear of gas except the off-curtain corner, where the ventilation is weak and may result in higher gas levels. The same trend was also noticed in the sump cut.

In slab cut, the two cases with 15% and 100% scrubber exhaust flow redirect back toward the face from the off-curtain side outlet can produce similar low gas ventilation effect. However, if considering their relatively high gas results in sump cut, those two configurations are not recommended for high gas mines.

In slab cut and sump cut, the evenly split 100% scrubber redirection cases did not show a lower gas environment with the two discharge angles (23º and 45º) and are not recommended for high gas mines.

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DISCLOSURE

The findings and conclusions in this manuscript are those of the authors and do not necessarily represent the views of the National Institute for Occupational Safety and Health (NIOSH). Mention of company names or products does not constitute endorsement by NIOSH.

REFERENCES

1. Taylor, C.D., Chilton J.E., Hall, E., and Timko, R.J. (2006), "Effect of Scrubber Operation on Airflow and Methane Patterns at the Mining Face", *Proceedings of the 11th U.S./North American Mine Ventilation Symposium*, June 5-7, University Park, PA, pp. 393-399.

2. Taylor, C.D., Chilton, J.E., and Goodman, G.V.R. (2010), "Guidelines for the Control and Monitoring of Methane Gas on Continuous Mining Operations", U.S. Department of Health and Human Services, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health, DHHS (NIOSH), publication No. 2010-141, Information Circular 9523, 75 pp, http://www.cdc.gov/niosh/mining/UserFiles/works/pdfs/2010-141.pdf.

3. Colinet, J.F., Rider, J.P., Listak, J.M., Organiscak, J.A., and Wolfe, A.L. (2010), "Best Practices for Dust Control in Coal Mining", U.S. Department of Health and Human Services, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health, DHHS (NIOSH) Publication No. 2010-110, Information Circular 9517, 76 pp, http://www.cdc.gov/niosh/mining/UserFiles/works/pdfs/2010-110.pdf.

4. Kissell, F.N. (2003), "Handbook for Dust Control in Mining", Pittsburgh, PA: U.S. Department of Health and Human Services, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health, DHHS (NIOSH) publication No. 2003-147, Information Circular 9465, 131 pp, http://www.cdc.gov/niosh/mining/UserFiles/works/pdfs/2003-147.pdf.

5. Organiscak, J. and Beck, T. (2013), "Examination of Redirected Continuous Miner Scrubber Discharge Configurations for Exhaust Face Ventilation Systems", *Transactions of the Society for Mining, Metallurgy and Exploration*, Vol. 332, No. 1, pp. 435-443.

6. Goodman, G.V.R., Taylor, C.D., Colinet, J.F., and Thimons, E.D. (2001), "Research by NIOSH for Controlling Respirable Dust and Methane Gas on Continuous Miner Faces", *Proceedings of the 7th International Mine Ventilation Congress*, June 17-22, Krakow, Poland, pp. 237-241.

7. Goodman, G.V.R., Beck, T.W., and Pollock, D.E. (2006), "The Effects of Water Spray Placement for Controlling Respirable Dust and Face Methane Concentrations", *Journal of the Mine Ventilation Society of South Africa*, Vol. 20, No. 2, pp. 56-63.

8. Jayaraman, N.I., Kissell, F.N., and Schroeder, W. (1984), "Modify Spray Heads to Reduce Dust Rrollback on Miners", *Coal Age*, Vol. 89, No. 6, pp.56-57.

9. Pollock, D. and Organiscak, J. (2007), "Airborne Dust Capture and Induced Airflow of Various Spray Nozzle Designs", *Aerosol Science and Technology*, Vol. 41, No.7, pp. 711-720.

10. Chilton, J.E., Taylor C.D., Hall, E.E., and Timko, R.J. (2006), "Effect of Water Sprays on Airflow Movement and Methane Dilution at the Working Face", *Proceedings of the 11th U.S./North American Mine Ventilation Symposium*, June 5-7, University Park, PA, pp. 401-406.

11. McPherson, M.J. (1988), "Effect of Controlled Recirculation on Methane Concentrations in Headings", *Society of Mining Engineers of AIME, 1987 Transaction*s Vol. 282, pp. 1864-1867.

12. Leach, S.J., and Slack, A. (1969), "Recirculation of Mine Ventilation Systems", *The Mining Engineer*, January 1969, pp. 227-234.

13. Bakke, P., Leach, S.J., and Slack, A. (1964), "Some Theoretical and Experimental Observations on the Recirculation of Mine Ventilation", *Colliery Engineering*, 41, 1964, pp. 471-477.

14. Yuan, L. and Smith, A.C. (2007), "Computational Fluid Dynamics Modeling of Spontaneous Heating in Longwall Gob Areas", *Transactions of the Society for Mining, Metallurgy and Exploration*, Vol. 322, pp. 37-44.

15. Ren, T.X., Balusu, R., and Humphries, P. (2005), "Development of Innovative Goaf Inertisation Practices to Improve Coal Mine Safety", *Aziz, N(ed), Coal 2005: Coal Operators' Conference*, University of Wollongong and the Australiasian Institute of Mining and Metallurgy, pp. 315-322.

16. Ren, T.X. and Balusu, R. (2008), "Innovative CFD Modeling to Improve Dust Control in Longwalls", *Aziz, N(ed), Coal 2008: Coal Operators' Conference*, University of Wollongong and the Australiasian Institute of Mining and Metallurgy, pp. 137-142.

17. Hargreaves, D.M. and Lowndes, I.S. (2007), "The Computational Modeling of the Ventilation Flows within a Rapid Development Drivage", *Tunnelling and Underground Space Technology*, Vol. 22, No. 2, pp. 150-160.

18. Wala, A.M., Vytla, S., Huang, G., and Taylor, C.D. (2007), "Mine Face Ventilation: a Comparison Against Benchmark Experiments for the CFD Code Validation", *Mining Engineering*, Vol. 59, pp. 49-55.

19. Kollipara, V.K., Chugh, Y. P., and Relangi, D.D. (2012), "A CFD Analysis of Airflow Patterns in Face Area for Continuous Miner Making a Right Turn Cut", *Proceedings of the SME annual meeting*, February 19-22, Seattle, WA, preprint, pp. 12-132.

20. Torno, S., Torańo, J., Ulecia, M., and Allende, C. (2013), "Conventional and Numerical Models of Blasting Gas Behavior in Auxiliary Ventilation of Mining Headings", *Tunnelling and Underground Space Technology*, Vol. 34, pp.73-81.

21. Zhou, L., Pritchard, C., and Zheng, Y. (2015), "CFD Modeling of the Methane Distribution at a Continuous Miner Face with Various Curtain Setback Distances", I*nternational Journal of Mining Science and Technology*, Vol. 25, Iss. 4, pp. 635-640, available: http://dx.doi.org/10.1016/j.ijmst.2015.05.018.

22. Zheng, Y. (2011), "Diesel Particulate Matter Dispersion Analysis in Underground Metal/Non-metal Mines Sing Computational Fluid Dynamics," *PhD Dissertation*, Missouri University of Science and Technology, Rolla, MO., 261 pp.

23. Xu, G., Luxbacher, K.D., Ragab, S., and Schafrik, S. (2013), "Development of a Remote Analysis Method for Underground Ventilation Systems Using Tracer Gas and CFD in a Simplified Llaboratory Apparatus," *Tunnelling and Underground Space Technology*, Vol. 33, pp. 1-11.

24. Zheng, Y., Organiscak, J.A., Zhou, L., Beck, T.W., and Rider, J.P. (2015) "CFD Analysis on Gas Distribution for Different Scrubber Redirection Configurations in Sump Cut", *2015 Transactions of the Society for Mining, Metallurgy & Exploration*, Vol. 338, pp. 423-432.

25. PMRD (2013), "Full Scale Continuous Miner Dust Gallery", Office of Mine Safety and Health Research Facilities in Pittsburgh, PA, http://www.cdc.gov/niosh/mining/content/facilities.html.

26. MSHA (2012), "Re-issue of I10-V-09 – Procedures for Evaluation of Requests to Make Extended Cuts with Remote Controlled Continuous Mining Machines", U.S. Department of Labor, Mine Safety and Health Administration, Procedure Instruction Letter No. I12-V-11, 11 pp, http://www.msha.gov/regs/complian/PILS/2012/PIL12-V-11.pdf.