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CFD analysis on gas distribution for different scrubber redirection configurations in sump cut

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Abstract

The National Institute for Occupational Safety and Health's Office of Mine Safety and Health Research recently developed a series of models using computational fluid dynamics (CFD) to study the gas distribution around a continuous mining machine with various fan-powered flooded bed scrubber discharge configurations. CFD models using 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 following scenarios are considered in this study: 100 percent of the discharge redirected back toward the face on the off-curtain side of the continuous miner; 100 percent of the discharge redirected back toward the face, but divided equally to both sides of the machine; and 15 percent of the discharge redirected toward the face on the off-curtain side of the machine, with 85 percent directed into the return. These models were compared against a model with a conventional scrubber discharge, where air is directed away from the face into the return. The CFD models were calibrated and 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 percent redirected, equally divided case. These models identified relatively high gassy areas

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Disclosure
The findings and conclusions in this report are those of the authors and do not necessarily represent the views of NIOSH.

around the continuous miner, which may not warrant their use in coal mines with medium to high methane liberation rates. This paper describes the methodology used to develop the CFD models, and the validation of the models based on experimental data.

Keywords

Gas distribution; CFD; CFD calibration and validation; CFD prediction

Introduction

Methane gas and respirable dust are two hazards frequently encountered at continuous-miner operations. An accumulation of both methane gas and coal dust may lead to massive explosions underground (Dubinski, Krause and Skiba, 2011), and overexposure to respirable coal dust can result in pneumoconiosis, commonly referred to as “black lung disease” in coal workers (National Institute for Occupational Safety and Health, 2008).

Current U.S. federal coal mine regulations limit concentrations of methane gas to below 1 percent at the face area and require exposures to respirable coal dust to be at or less than an 8-hr shift average of 2.0 mg/m^3. Beginning Aug. 1, 2016, the overall respirable dust standard in coal mines is reduced to 1.5 mg/m^3, from 2.0 mg/m^3, for full shift sampling. If the quartz concentration exceeds 100 μg/m^3, the dust standard becomes more stringent, reducing the allowable concentration to the value of 10 divided by the percent quartz (Code of Federal Regulations, 2014).

The most effective way to prevent high methane gas and dust concentrations is to deliver sufficient fresh air 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 (Taylor et al., 2006,2010; Colinet et al., 2010).

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 (Kissell, 2003). Several coal mines having negligible gas emissions in higher coal seams, 2.4 to 3.0 m (8 to 10 ft) thick, with exhaust tubing systems redirect the scrubber exhaust back toward the face in an effort to improve dust collection (Organiscak and Beck, 2013). Since the redirection of scrubber exhaust has not been approved by the Mine Safety and Health Administration (MSHA) for use in thinner and gassier coal seams with ventilation curtains, the National Institute for Occupational Safety and Health (NIOSH) studied the redirected scrubber exhaust techniques for dust and gas control in a full-scale continuous-miner gallery to assess its potential for industry-wide application.

Many of the previous computational recirculation and experimental research have focused on general-body concentrations. They assumed the methane and air are completely mixed at regional areas in the mine (McPherson, 1988; Leach and Slack, 1969). Some studies also examined localized recirculation devices, such as fans, compressed-air injectors and sprays, to increase air velocities and induce air mixing to reduce gas stratification (Bakke, Leach and Slack, 1964). Although these studies are insightful and provide some prescribed measures for recirculation practices, they do not necessarily provide insights into the gas mixing and concentration gradients at the mining face using scrubber configurations with exhaust curtain.

For a continuous-miner face, previous studies have concluded that the behavior of gas and respirable dust is complex (Goodman et al., 2001; Goodman, Beck and Pollock, 2006). 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 (Jayaraman, Kissell and Schroeder, 1984; Pollock and Organiscak, 2007; Chilton et al., 2006). To understand these behaviors in a complex continuous-miner environment and to evaluate the effectiveness of various control techniques, numerical modeling has become a necessary supplement to laboratory experiments and field studies.

Computational fluid dynamics (CFD) simulations have been successfully used in mining research to detect spontaneous combustion and apply inertization in gob areas (Yuan and Smith, 2007; Ren, Balusu and Humphries, 2005), study airflow patterns and gas concentrations in common continuous-miner ventilation configurations (Sullivan and Heerden, 1993; Hargreaves and Lowndes, 2007; Wala et al., 2007; Kollipara, Chugh and Relangi, 2012; Torno et al., 2013), investigate scrubber intake designs for longwall dust control (Ren and Balusu, 2008), visualize diesel emissions dissipation in underground metal/nonmetal mines (Zheng, 2011), and estimate a mine’s ventilation status after a disaster (Xu et al., 2013). CFD modeling has become a powerful tool for understanding airflow movement and gas/dust behavior in a complicated three-dimensional environment. It can also provide useful information for the initial concept testing of new ideas and equipment for gas and dust control.

The objective of this study is to use CFD techniques to build a numerical model of the Office of Mine Safety and Health Research (OMSHR) continuous-miner test gallery and validate the model using experimental findings from prior OMSHR laboratory dust control research. The effects of different scrubber redirection configurations on gas distribution were evaluated for four experimental cases and one prediction case. The simulation procedure and results are presented and discussed in the paper. Our study extends the knowledge of airflows at the continuous-miner face, identifying regions of high gas concentrations to guide future testing and design of control technology. The prediction of airflows for a potential redesign is demonstrated, showing the technique’s ability to augment laboratory testing.

Methods

Laboratory experiments

Laboratory experiments were previously conducted by OMSHR to test the effect of scrubber redirection on gas and dust distribution using an exhaust curtain ventilation system (Organiscak and Beck, 2013). The layout of this full-scale continuous-miner facility is shown in Fig. 1 with an exhaust ventilation curtain extended to within 12.2 m (40 ft) of the mining face (OMSHR, 2013). A 12.2-m (40-ft) distance represents the largest curtain setback typically encountered while mining extended (deep) cuts (MSHA, 2012). 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. A 1.2 m (3.9 ft) wide by 6.1 m (20 ft) long slab is placed on the off-curtain side of the mining face to simulate a block of coal in the slab portion of the cut. Face airflow was measured by moving traverse at the inlet of the curtain, 0.91 m (3 ft) wide, 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 Fig. 1. The scrubber was operated at a flow rate of 3.3 m^3/s (7,000 cfm) for various scrubber configurations. The scrubber exhaust discharge configurations examined were:

- Conventional: 100 percent of the air directed outby on the curtain side of the face from scrubber exhaust location 1.
- 85/15: 15 percent of the air redirected to the off-curtain side of the mining machine from exhaust location 3, and 85 percent of the air directed outby on curtain side of the face from exhaust location 1.
- 50/50: 50 percent of the air directed up each side of the mining machine toward the face from exhaust locations 2 and 3, respectively.
- 100 percent R: 100 percent of the air directed toward the face on the off-curtain side of the mining machine from exhaust location 3 (Organiscak and Beck, 2013).

External sprays consisted of 15 top-mounted boom sprays (Sprays Bar in View 1 of Fig. 1) directed at the top of the rotating drum, three under-boom throat sprays (View 2 of Fig. 1) directed at the loading pan, and three sprays on each side of the cutter boom directed at the drum's end rings (Fig. 1 and View 1 of Fig. 1). 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.

Sulfur hexafluoride (SF_6) gas was introduced in front of the rotating cutting drum from two tubes to the left and right side (View 1 of Fig. 1). SF_6 gas measurements were recorded at the curtain and off-curtain side of the cutter boom (Gas 1 and Gas 2, as shown in Fig. 1 and View 1 of Fig. 1). Also, gas measurements were recorded inside the scrubber duct close to the duct junction (Gas 3 in Fig. 1) and in the return air course (Gas 4 in Fig. 1). For the experiment and this study, all SF_6 results are limited to comparing gas level changes around the continuous mining machine for the different scrubber configurations and are not reflective of actual methane emission at any particular mine.

CFD modeling

CFD simulations were conducted with ANSYS FLUENT 13.0 simulation software (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. A geometric model representing the cases was built according to the design measurements of the full-scale continuous-miner gallery. The simulation domain was discretized into about 1.4 million hexahedral and tetrahedral control volumes (cells). The size of the mesh ranges from a minimum of 2.5 cm (1.0 in.) around the mining machine to a maximum of 10.2 cm (4.0 in.) outby the face.

The locations of the boundary conditions are illustrated in Fig. 1. Fresh air entering the mining face/simulation domain is depicted 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, an interior plane, or a fan was placed at each of the three scrubber outlets. For example, in the 50/50 scenario, air was discharged evenly from outlet locations 2 and 3. The boundary condition for scrubber exhaust location 1 was a wall to prevent airflow. At outlet location 2, a fan condition was used to compensate the higher shock loss through its branch, while an interior plane was used to allow airflow through outlet location 3.

To model the air-moving effects of the machine-mounted water sprays, a fan condition as 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. All the other boundaries within the domain were defined as interior planes or walls.

For the boundary conditions, entry inlet, entry outlet and velocity speed of gas feeders are known from the experiment. The scrubber can be considered as known by adjusting the boundary conditions at the scrubber inlet and three discharge locations to provide the airflow according to the experimental configuration. The unknown boundaries are the fan condition at the four spray locations and the mass fraction of gas from the gas feeders. These were obtained by iterations of the conventional scrubber discharge case and confirmed by the other three experimental cases.

Of the four experimental cases, the conventional scrubber discharge case was selected to calibrate the model because this configuration results in less complex airflow patterns in the face region. During the calibration process, the turbulence model and solution method were evaluated and the unknown boundary conditions were adjusted to make the gas concentration at the four gas monitor locations agree with the experimental results.

The parameters of the CFD models are listed in Table 2. The same settings, except for the scrubber parameters, were used in all four experimental cases to validate the gas distribution study. The repeated settings include the entry inlet velocity and outlet pressure, fan condition with the same pressure increase in all four spray locations, and the same gas feeder velocity and mass fraction number. For the scrubber inlet and exhaust outlets, the boundary conditions were adjusted to match the experimental airflow rates at the discharge outlets for different cases.

For each case, the CFD-modeled airflow patterns were examined for agreement with air currents observed by smoke visualization for the corresponding laboratory experiment. After the calibration and validation process, the prediction case used the same simulation parameters to study the gas distribution.

Results and discussion

Comparison of CFD modeling with laboratory experiments

Table 3 shows that the CFD simulation cases agreed well with the experimental data (within ±15 percent difference) at the four gas monitoring locations. Also, the airflows revealed by simulation agreed with the visually observed smoke flow patterns. Because of the agreement in both calculations and observations, the simulation results shown below can be used with reasonable accuracy to represent the gas distribution in the continuous-miner gallery.

Conventional, 100 percent exhaust discharge—In the conventional case, 100 percent of scrubber exhaust airflow came from scrubber outlet 1 (Fig. 1), which is the normal discharge pattern of the scrubber. The fresh airflow pattern shown in Fig. 2 revealed that as the air flowed toward the face, part of the airflow went directly to the return, while a portion was drawn toward the scrubber inlets. Most of the fresh air that flowed toward the face went to the left side (curtain side) of the entry through the left scrubber inlet. The right side of the entry was obstructed by the simulated block of coal in the slab portion of the cut. This fresh airflow pattern reduced the amount of gas on the left side of the face area (0.75 ppm from the experiment, 0.71 ppm from CFD), as shown in Fig. 3. The gas accumulation was approximately 10 times higher on the right side of the face area (off-curtain side, 7.38 ppm experiment, and 6.41 ppm CFD). The air and gas mixture drawn into the scrubber was discharged from exhaust location 1 and hit the wall close to the curtain, creating turbulence in that area.

It is noticeable in Fig. 3 that a portion of the high level gas plume missed the scrubber inlets on the off-curtain side and was pushed backward. This is mainly caused by the airflow induced from the top-mounted boom sprays.

85/15, 85 percent conventional exhaust discharge with 15 percent scrubber redirection—In the 85/15 case, 85 percent of airflow, at a rate of 2.83 m^3/s (6,000 cfm), was exhausted from scrubber outlet 1 and the other 15 percent, at a rate of 0.47 m^3/s (1,000 cfm), from outlet 3 (off-curtain side). Compared with the conventional scrubber flow, the 85/15 configuration induced more airflow to the right side of the face area, as shown in Fig. 4. The gas concentration near the front right corner of the machine (off-curtain side) was reduced by this arrangement, as shown in Fig. 5. However, the airflow from the curtain and off-curtain side of the machine flowed in opposite directions near the face region—a scenario that indicated recirculation in the central face region. As a result, it can be observed from Fig. 5 that the gas level could be relatively high both above and in front of the drum.

When compared with the conventional case, this exhaust redirect configuration may result in higher gas levels in the central region above the cutting drum, where frictional ignition sources are known to exist. However, the actual gas levels of this region may not be predicted accurately by the current study since the rotation of the cutting drum was disregarded in the simulation. The rotation of the drum may help mix the gas and air more uniformly in the drum region, which could lower gas levels.

50/50_23D, 50 percent redirection to curtain side and 50 percent to off-curtain side—In this 100-percent scrubber redirection case, with 50/50 distribution of the scrubber discharge, 50 percent of airflow was discharged from scrubber outlet 2, and 50 percent from scrubber outlet 3. The discharge angles of both outlets were approximately 23 degrees away from the body of the continuous miner.

The outlet area is 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 continuous miner, as the airflow discharged from the left outlet caused the air to swirl toward the off-curtain side of the entry in the face area. Due to the obstruction caused by the block of coal in the slab portion of the cut, only a small part of the air was directed from the right scrubber outlet toward the face. The airflow from the left scrubber outlet dominated the ventilation of the face area, as shown in Fig. 6.

In the rear of the continuous miner, airflow from the right scrubber outlet hit the slab, right wall, and floor. Most of the airflow went directly toward the return at the roof level. Part of the fresh air from the entry inlet flowed toward the face close to the floor level, while a portion of fresh air was directed toward the return without ventilating the face (Fig. 6).

Recirculation in the face area, caused mostly by the left scrubber outlet discharge, resulted in higher and more uniform gas levels in the face region compared with the previous two simulation cases, as shown in Fig. 7. The highest gas level was observed on the off-curtain corner due to less air reaching the face from the right scrubber outlet. The CFD drawing shows that the scrubber reused some of the airflow from its exhaust, reducing the amount of fresh air reaching the face.

100 percent R, 100 percent redirection to off-curtain side—In this 100-percent scrubber redirection case, 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).

It can be observed from Fig. 8 that airflow from the right scrubber outlet hit the slab, right wall, and floor. Most of the exhaust flow traveled toward the return at the roof level and some of it flowed toward the face after hitting the left wall, while a quantity of the fresh air from the entry inlet went toward the face underneath that flow. A portion of the discharge from the right scrubber outlet combined with the fresh air traveling toward the face, and flowed from the off-curtain to curtain side of the entry.

Since the air in the face area flowed from right to left, gas was pushed toward the front left side of the face area, as shown in Fig. 9. Overall, this redirected configuration recirculated the scrubber exhaust, resulting in gas levels that were uniformly higher than the conventional and 85/15 simulation scenarios. Similar to the 50/50 case above, the scrubber recirculated some of the airflow from its exhaust, reducing the amount of fresh air reaching the face.

Prediction of face conditions using CFD

By calibrating and 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 OMSHR researchers have observed an underground U.S. mine with height of 3.0 m (10 ft) redirecting the discharge from the scrubber, as in the 50/50 experimental case, but at an angle of 45 degrees from the body of the continuous miner. 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. These results can be further compared with those obtained in the prior 50/50_23D CFD simulation with scrubber outlets angled at 23 degrees to identify regions of interest and estimate any possible changes in gas concentrations.

At the larger angle of 45 degrees, airflow directed toward the face from the right scrubber outlet was totally blocked by the right wall and slab (Fig. 10a). The airflow from the left scrubber outlet dominated the ventilation of the face area and the airflow swept the face from left to right. As shown in Fig 11a, this flow pattern pushed the gas toward the off-curtain side of the entry. For the 23-degree simulation case shown in Fig. 10b, a portion of the airflow from the right scrubber outlet traveled toward the face and ventilated the off-curtain corner. As a result, Fig. 11a shows that gas levels in the right corner of the face area were higher and covered a larger area in the 45-degree prediction case than in the 23-degree case in Fig. 11b. In Figs. 10a and 10b, the colored arrow lines represent the course of different particles released from the middle of the scrubber.

The gas concentrations for all four sampling locations are listed in Table 4. In the table, the simulated gas levels for 45-degree case are listed on the second line. The next two lines list the simulated gas concentrations for the 23-degree discharge angles and the difference between the 45-degree and 23-degree simulations for each sampling location. The simulated gas concentration at off-curtain location 2 is predicted to be nearly 40 percent higher when using the 45-degree scrubber outlets.

Conclusions

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

Based on current experimental settings, simulation results showed that for scrubber redirection on a 2.1-m (7-ft) coal seam continuous-miner face, the 50/50 and 100 percent R configurations produced uniformly higher gas levels in the face area when compared with the conventional and 85/15 partial redirect configurations. However, the conventional and 85/15 arrangements had a tendency to produce gas hot spots with higher relative gas concentrations in the active face, drum and cutter boom regions. Based on the results seen with the tested scenarios, the presence of high gas regions could not warrant the usage of redirected scrubber configurations toward the face in coal mines with detectable methane liberation rates. These simulations predicted the gas distribution with reasonable accuracy and indicate that it may be beneficial to use the same geometric model to evaluate dust levels during scrubber redirection in low/medium coal seam mines. The CFD model and boundary conditions obtained in the study may be further applied to evaluations of future dust and gas control technologies involving water sprays and other airflow devices, ventilation plans or work practices.

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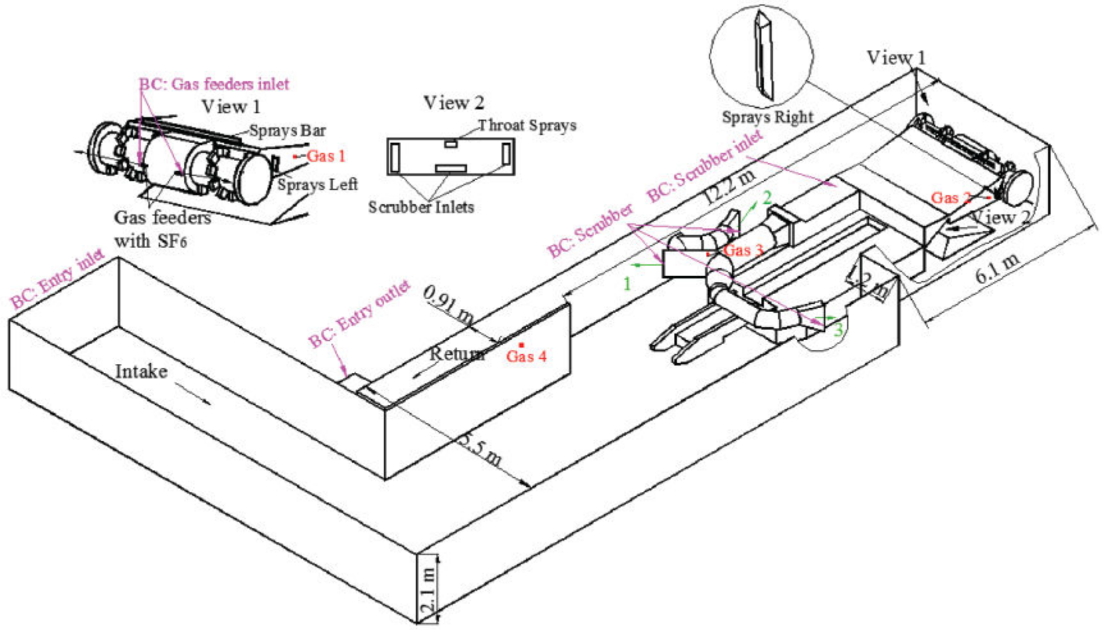

Figure 1.

Layout and dimensions of the full-scale continuous-miner gallery for scrubber redirection experiments, with the locations of boundary conditions (BC) also shown.

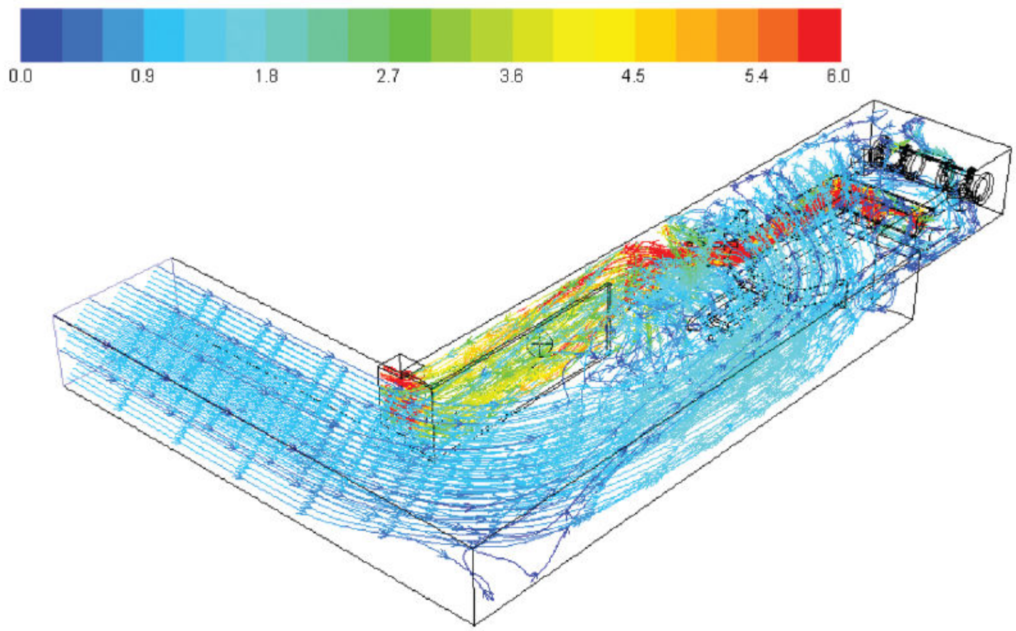

Figure 2.
Pathline of fresh airflow (conventional), different colored arrow lines representing the velocity (0.0-6.0 m/s) of different particles released from the entry inlet.

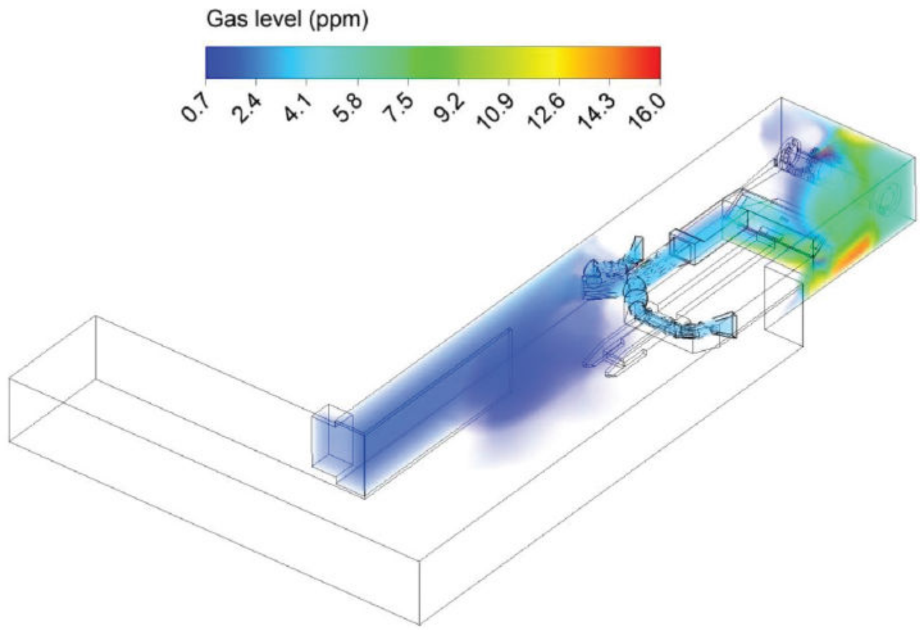

Figure 3.
Gas concentrations for simulation of conventional scrubber discharge, gas level: 0.7-16.0 ppm.

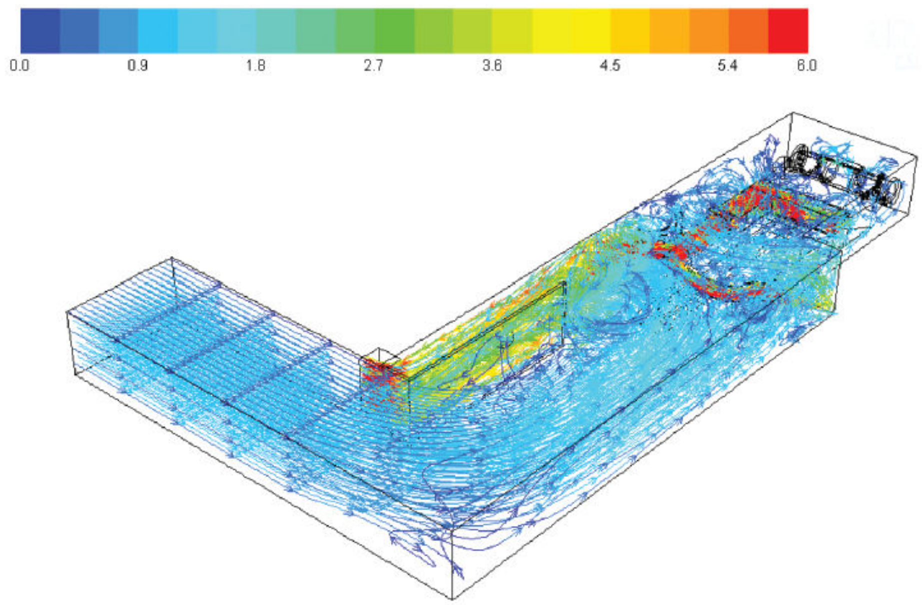

Figure 4.
Pathline of fresh airflow (85/15), different colored arrow lines representing the velocity (0.0-6.0 m/s) of different particles released from the entry inlet.

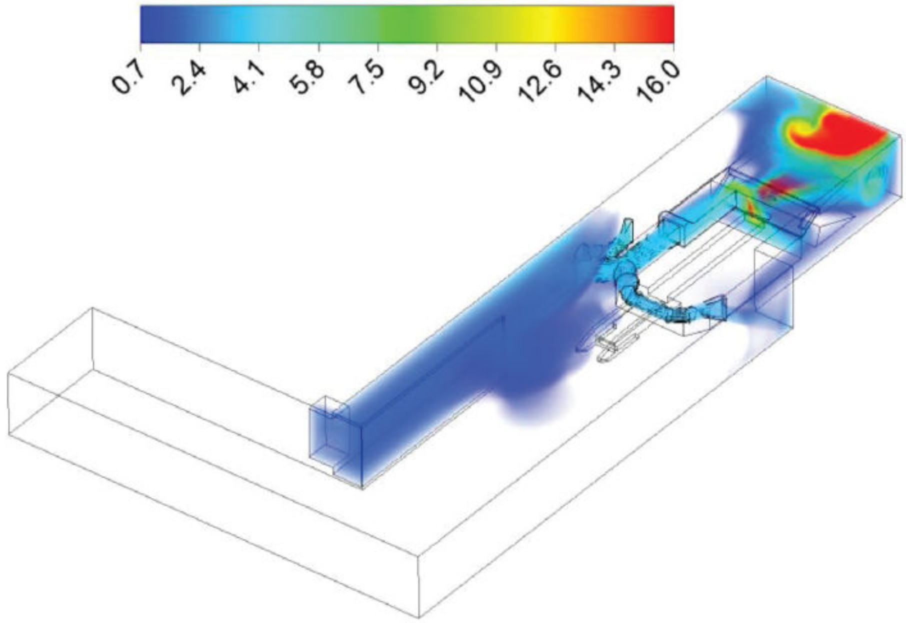

Figure 5.

Gas concentrations for simulation of 15 percent scrubber redirection and 85 percent conventional scrubber discharge, gas level from 0.7 to 16.0 ppm.

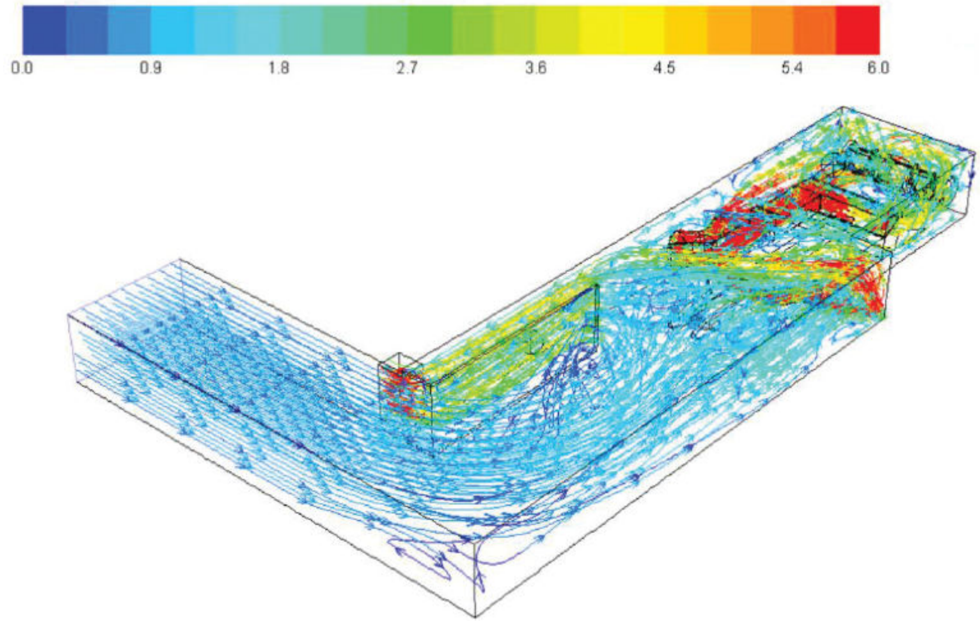

Figure 6.

Pathline of fresh airflow (50/50_23D), different colored arrow lines representing the velocity (0.0-6.0 m/s) of different particles released from entry inlet.

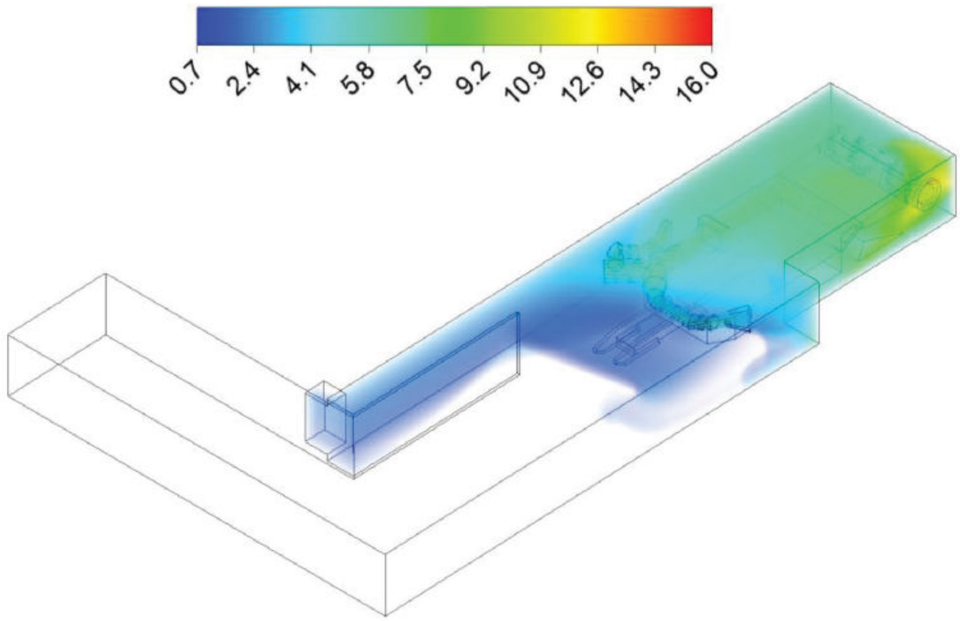

Figure 7.

Gas concentrations for simulation of evenly split 100 percent scrubber redirection, gas level from 0.7 to 16.0 ppm.

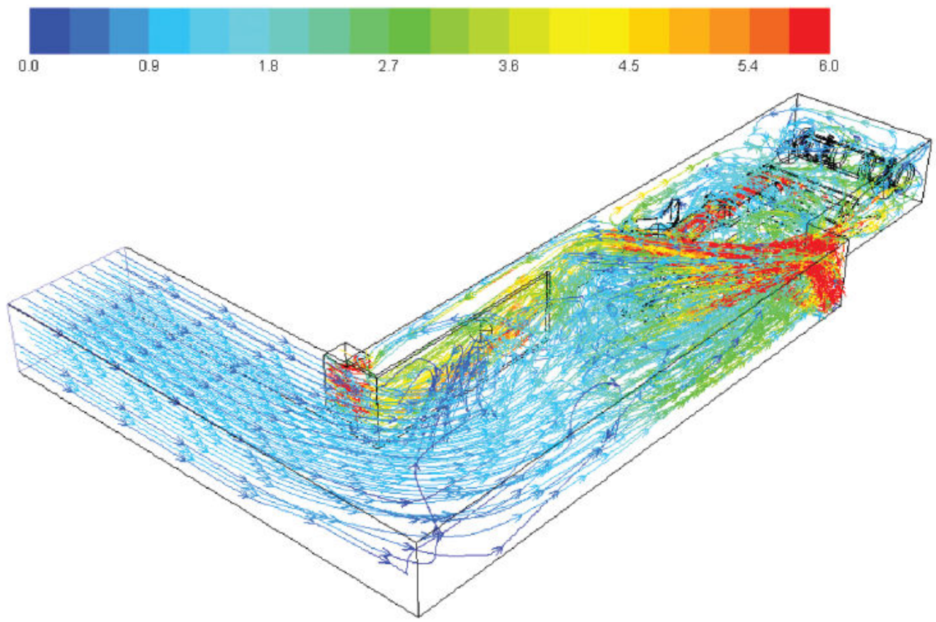

Figure 8.

Pathline of fresh airflow (100 percent R), different colored arrow lines representing the velocity (0.0-6.0 m/s) of different particles released from the entry inlet.

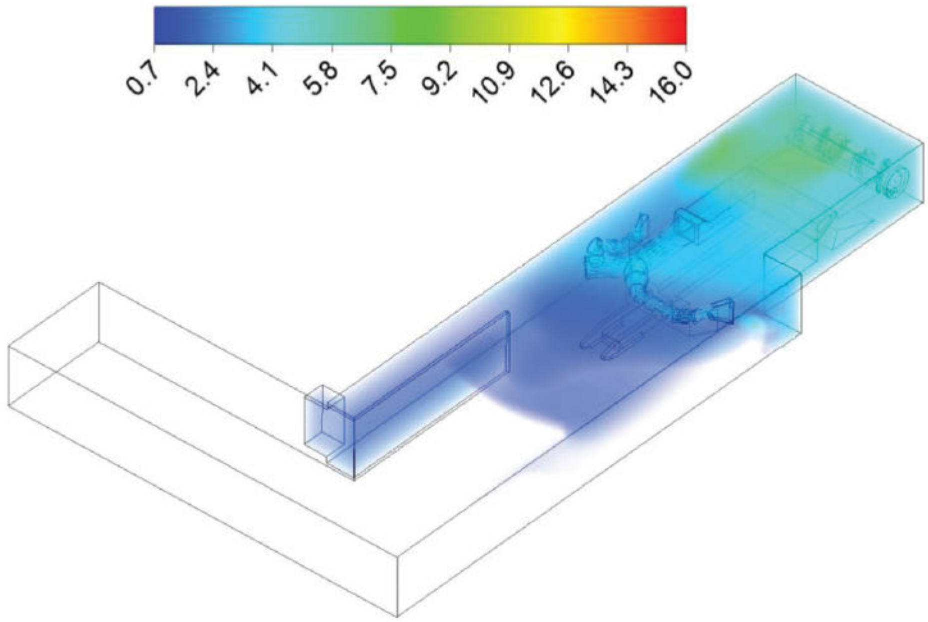

Figure 9.

Gas concentrations for simulation of 100 percent redirected scrubber discharge to off-curtain side, gas level from 0.7 to 16.0 ppm.

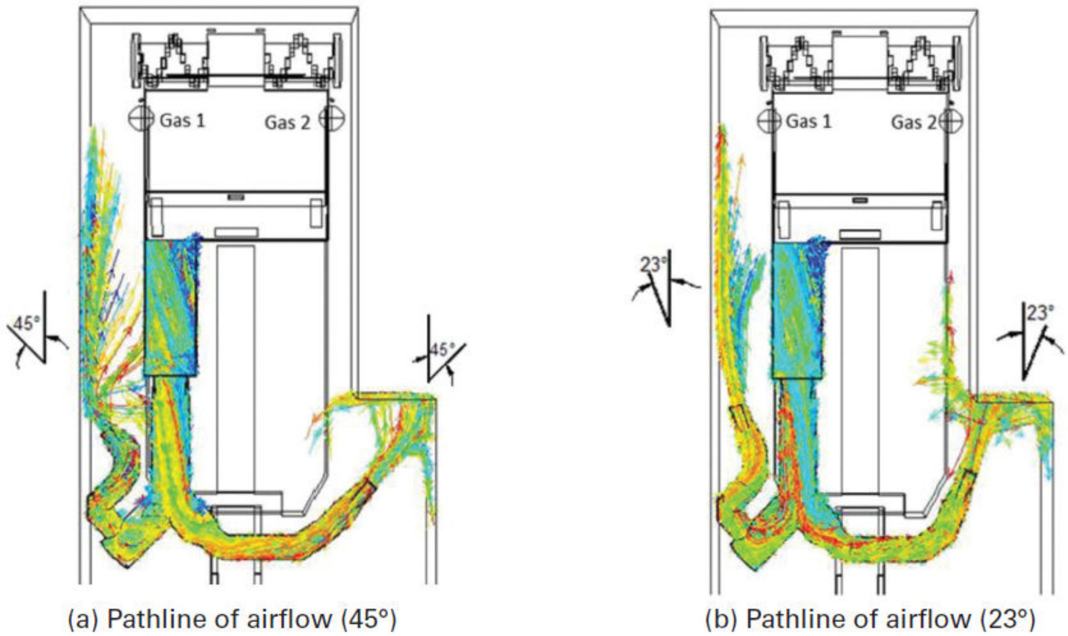

Figure 10.
Comparison of pathline for 45° and 23° outlets (50/50).

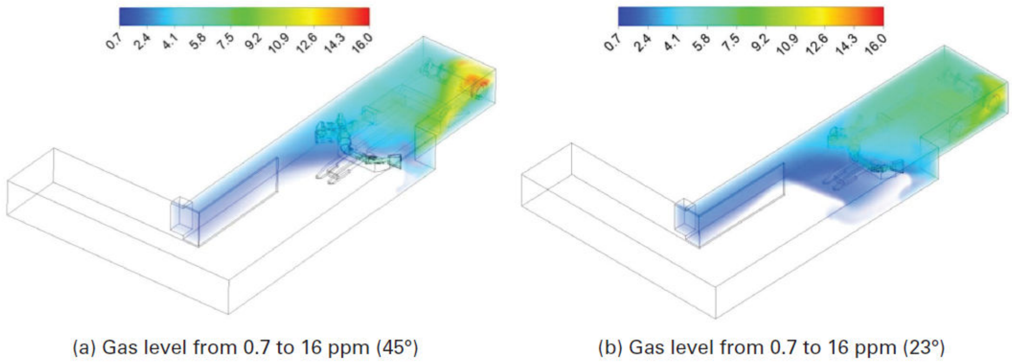

Figure 11.

Comparison of gas concentrations for 45° and 23° outlets (50/50).

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Table 1

Simulation cases with different scrubber redirect configurations.

Study cases	Description
Conventional	100 percent airflow discharged from scrubber exhaust location 1.
85/15	85 percent airflow discharged from scrubber exhaust location 1 and the other 15 percent from scrubber exhaust location 3.
50/50_23D	50 percent airflow discharged from scrubber exhaust location 2 and the other 50 percent airflow from scrubber exhaust location 3, the discharge angle was 23° from the body.
100 percent R	100 percent airflow discharged from scrubber exhaust location 3.
50/50_45D	50 percent airflow discharged from scrubber exhaust location 2 and the other 50 percent airflow from scrubber exhaust location 3, the discharge angle was 45° from the body.

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Table 2

Input parameters for the CFD models in this study.

Simulation setups	Parameter descriptions
Simulation model	Species transport model without reactions.
Turbulence model	k-ε, realizable, enhanced wall condition.
Boundary	Entry inlet: Velocity inlet, 0.98 m/s (193 fpm).
conditions	Entry outlet: Pressure outlet, 0 Pa.
	Sprays: Fan, 40 Pa.
	Scrubber: Fan/wall/interior plane, depending 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; for others: 2nd order upwind.

Table 3

Percent difference (Diff.) in gas concentrations between experiment (Exp.) and CFD simulation (CFD).

Experiment cases		Gas 1*	Gas 2	Gas 3	Gas 4
Conventional	Exp. (SF_6 ppm)	0.75	7.38	2.82	1.51
	CFD (SF_6 ppm)	0.71	6.41	2.94	1.40
	Diff. (%)	−5.3	−13.1	4.3	−7.3
85/15	Exp. (SF_6 ppm)	1.19	7.26	3.23	1.48
	CFD (SF_6 ppm)	1.24	6.28	3.62	1.40
	Diff. (%)	4.2	−13.5	12.1	−5.4
50/50_23D	Exp. (SF_6 ppm)	7.26	10.03	7.74	1.62
	CFD (SF_6 ppm)	6.70	9.19	8.14	1.65
	Diff. (%)	−7.6	−8.4	5.3	2.1
100% R	Exp. (SF_6 ppm)	8.28	4.73	5.85	1.34
	CFD (SF_6 ppm)	7.11	4.75	6.26	1.41
	Diff. (%)	−14.1	0.4	7.0	5.2

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

Table 4

Predictions of gas levels 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)	5.56	12.91	7.1	1.45
50/50_23D CFD (SF_6 ppm)	6.70	9.19	8.14	1.65
Diff. (%)	−17.0	40.5	−12. 8	−12.1