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CFD gas distribution analysis for different continuous-miner scrubber redirection configurations

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Abstract

The U.S. National Institute for Occupational Safety and Health (NIOSH)'s Pittsburgh Mining Research Division (PMRD) recently developed a series of models using computational fluid dynamics (CFD) to study gas distribution around a continuous mining machine 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 percent of the discharge redirected back toward the face on the off-curtain side; 100 percent of the discharge redirected back toward the face, but divided equally to both sides; and 15 percent of the discharge redirected toward the face on the off-curtain side, with 85 percent directed toward the return curtain. These models are compared against a model with a conventional scrubber discharge where air is directed away from the face into the return. The models were validated against experimental data, proving to accurately predict sulfur hexafluoride (SF_6) gas levels at four gas monitoring locations. This study includes a predictive simulation examining a 45° scrubber angle compared with the 23° angle for the 100 percent redirected, equally divided case. This paper describes the validation of the CFD models based on experimental data of the gas distribution results.

Keywords

Computational fluid dynamics (CFD); Gas distribution; Scrubber discharge; FLUENT

Introduction

To control methane gas and dust concentrations in continuous mining operations, it is important to provide sufficient quantity of fresh air from the end of the tubing or curtain to the active face. In this region, operating machine-mounted water sprays and fan-powered,

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flooded bed scrubbers can significantly increase the amount of airflow reaching the face (Taylor, Chilton and Goodman, 2010; Colinet et al., 2010).

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 (Kissell, 2003). Currently, several coal mines with negligible gas emissions redirect the scrubber discharge back toward the face in an effort to improve dust collection. Those mines have higher coal seams, 2.4 to 3.0 m (8 to 10 ft) thick, and are ventilated by exhaust tubing systems. To assess its potential for industry-wide application, the U.S. National Institute for Occupational Safety and Health (NIOSH) studied this redirected scrubber exhaust technique for dust and gas control in a full-scale continuous mining machine gallery (Organiscak and Beck, 2013).

In continuous mining machine faces, 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, movement pattern of the ventilation air, interactions with the continuous mining machine, and water droplets created by the external water spray systems (Goodman, Beck and Pollock, 2006; Pollock and Organiscak, 2007; Chilton et al., 2006). To understand these behaviors in a complex continuous mining machine environment and to evaluate the effectiveness of various control techniques, numerical modeling has become a necessary supplement to laboratory experiments and field studies.

In mining research, computational fluid dynamics (CFD) has been used to detect spontaneous combustion and apply inertization in gob areas (Yuan and Smith, 2014; Marts et al., 2013; Wedding, 2014), investigate longwall dust control (Ren and Balusu, 2008), study airflow and gas distribution in common continuous mining machine ventilation configurations (Kollipara, Chugh and Relangi, 2012; Torno et al., 2013; Zhou, Pritchard and Zheng, 2015), visualize diesel emissions dissipation in underground metal and 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, gas and dust behavior in complicated three-dimensional environments.

The objective of this study is to use CFD techniques to build numerical models of the continuous mining machine test gallery of NIOSH’s Pittsburgh Mining Research Division (PMRD) and validate the models against experimental findings from prior PMRD laboratory research. Experimental and simulated studies of gas distributions in the face area of a sump cut were conducted previously, and the results were reported in Zheng et al. (2015).

This study reexamines the same scrubber discharge cases as the sump cut with the continuous mining machine positioned in the slab cut position, and without the effect of the block of coal at the off-curtain side. As in the sump-cut study, four experimental cases and one predictive 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 examined and can be used to identify the factors affecting airflow distribution in the continuous mining machine face area.

Methods

Laboratory experiments

The detailed layout of the full-scale continuous mining machine facility is shown in Fig. 1 with an exhaust ventilation curtain extended to 12.2 m (40 ft) of the mining face. 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 14CM 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. Face airflow was measured by traversing at the inlet of the exhaust 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 onboard scrubber with modified discharge ducts. 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 the cutter boom (view 2 in Fig. 1). The following scrubber discharge configurations were examined:

1. Conventional: 100 percent of the air directed outby on the curtain side of the face from scrubber exhaust location 1.
2. 85/15: 15 percent of the air redirected to the off-curtain side of the continuous mining machine from exhaust location 3, and 85 percent of the air directed outby on curtain side of the face from exhaust location 1.
3. 50/50_23D: 100 percent of the discharge redirected back toward the face, divided equally from exhaust location 2 and 3. The discharge angle was 23° from the body.
4. 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.

The 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°, as indicated by the detailed view of sprays on the right.

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

CFD modeling

CFD simulations were conducted with FLUENT 15.0 (ANSYS Inc., Canonsburg, PA), and species transport model without reactions was used to study the gas distribution in the mining face area. Five simulation cases were considered with steady-state analysis, four of which were based on the laboratory experiment settings while the fifth used a modified scrubber discharge angle, 50/50_45D, where 100 percent of the discharge redirected back toward the face was divided equally from exhaust locations 2 and 3 and the discharge angle was 45° from the body.

This study represents the slab (second) cut of the continuous mining machine face. The locations of the boundary conditions are illustrated in Fig. 1. 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 is placed behind the exhaust return curtain. The scrubber's airflow is controlled at four locations according to the different simulation scenarios. At the scrubber inlet, a fan condition is assigned to draw air into the system. In order to model each case, a wall, or an interior plane, or a fan is 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 is placed at the four spray locations, representing the nozzle-induced airflows. For the SF_6 gas feeders, a velocity inlet is assigned with a fixed velocity and fixed mass fraction of gas. All the other boundaries within the domain are defined as interior planes or walls. The meanings and locations of different boundary conditions are the same as those obtained from the calibration process in the sump-cut study (Zheng et al., 2015).

Results and discussion

Comparison of CFD modeling with laboratory experiments

Table 1 shows that the CFD simulation cases agreed well with the experimental data with differences of less than ±15 percent 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 continuous mining machine gallery.

Case study 1. Conventional, 100 percent discharge—In the conventional case, 100 percent of scrubber discharge airflow comes from scrubber outlet 1 (Fig. 1), which is the normal discharge pattern of the scrubber. Figure 2a shows the airflow pattern where the ventilating air flows toward the face and some of the airflow goes directly to the return while a portion is drawn toward the three scrubber inlet 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) are divided among the left, middle and right scrubber openings, respectively. As a result, it can be observed from Fig. 2a that most of the air that flows toward the face goes 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 are consistent for all of the other simulation cases studied.

In the right corner of the continuous mining machine face, there was a recirculation of air introduced by the sprays on top of the continuous mining machine, which has a high gas concentration level. Some of the fresh airflow moving toward the face from the right top and side of machine dilutes this recirculation zone. However, this fresh airflow is not enough and cannot penetrate the recirculation zone.

This airflow pattern reduces the gas level on the left side of the face area to 0.78 ppm in the experiment and 0.73 ppm in CFD simulation (Fig. 3a). The gas accumulation is eight times higher on the right side of the face area (off-curtain side) at 6.43 ppm in the experiment and 6.37 ppm in the CFD simulation.

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

The airflow from the right to the left side of the face reduces gas concentration near the front right corner of the machine (off-curtain side), compared with the conventional simulation results (Fig. 3b). At the same time, the gas migrates to the left side of the machine and increases the gas concentrations at gas sampling location 1.

Case study 3. 50/50_23D, 50 percent redirection to curtain and 50 percent to off-curtain side at 23°—In this case study, 100 percent of the scrubber discharge is redirected toward the face, 50 percent of the airflow is discharged from scrubber outlet 2 and 50 percent from scrubber outlet 3. The discharge angles of both outlets are approximately 23° away from the body of the continuous mining machine.

The outlet area measures 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). This configuration creates a large area of turbulence and recirculation in the front of the continuous mining machine. Figure 2c shows the airflow traveling down the ribs on the left and right sides of the continuous mining machine, then crossing the face, which creates the turbulence and recirculation at the left side of the cutting drum.

Because the flow of the discharged air creates multiple re-circulation zones in the face area, high levels of uniformly distributed gas are evident in the face region compared with the previous two simulation cases (Fig. 3c). The highest gas level is observed on the left side of the cutting drum where the two turbulent airflow outlets merge.

Case study 4. 100 percent R, 100 percent redirection to off-curtain side—In this case study, all of the scrubber discharge is from the off-curtain side, right outlet 3 with a velocity of 35.56 m/s (7,000 fpm). Figure 2d shows that airflow from the right scrubber outlet passes down the right side of the entry, across the face area, up the left side of the entry and then behind the curtain. As shown in Fig. 3d, a portion of the discharged airflow bypasses the inlet to the exhaust curtain and pushes the gas outby the curtain inlet, which creates a huge recirculation zone next to the curtain. The airflow pushes the gas to the left side of the entry, increasing the gas concentrations in the left corner of the face.

Prediction of face conditions using CFD

Using these validated CFD models, it is now possible to predict the gas distributions in other simulations 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) cut height redirecting 100 percent of the scrubber discharge toward the face from both sides of the continuous mining machine with a 45° angle. This configuration is similar to the 50/50_23D simulation case but with the scrubber discharge angle of 45° from the body of the continuous mining machine. This section uses CFD to predict the possible outcome when implemented in a 2.1-m (7-ft) coal seam face — simulation 50/50_45D. For all of the four previous experimental cases, scrubber outlet 1 was always pointing toward the rib at 45°, and the redirected outlets 2 and 3 were all oriented at 23° away from the continuous mining machine body.

Figure 4a shows the results with the scrubber discharge angled at 45° (50/50_45D). Airflow from the right scrubber outlet moves away from the right rib and spreads across the right side of the continuous mining machine. This airflow flows toward the three scrubber inlet openings and the face, which dominates the airflow from right to left underneath the cutter boom. Most of the airflow from the left scrubber outlet flows close to the left rib and sweeps the face from left to right. This airflow dominates the ventilation at the face above the cutter boom. Figure 5a shows that the airflow from the left outlet moves the gas toward the right side of the entry above the cutting drum, a portion of the gas then flows down-ward as it reaches the right rib and is controlled by the flow from the right scrubber outlet afterward to go underneath the cutter boom.

Case study 50/50_23D shows most of the airflow from the right scrubber outlet travels toward the face and encounters the airflow from the left scrubber outlet close to the left side of the cutting drum (Fig. 4b). Figure 5 shows the difference in gas concentrations in the entry for both of the simulation cases.

The gas concentrations for all four sampling locations are listed in Table 2. The simulated gas concentration at the left-side gas sampling location 1 is predicted to be 48.02 percent higher while the right-side gas sampling location 2 is predicted to be 116.52 percent higher when the scrubber discharge is angled at 45° compared with a 23° discharge angle.

Discussion

This study investigated the gas distribution around the continuous mining machine face in the slab cut (second cut). Together with the sump cut (first cut) from previous research, comparisons of the experimental data with simulation results at the four sampling locations are presented in Fig. 6.

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

To improve the off-curtain corner, 15 percent of the exhaust airflow — 0.47 m^3/s (1,000 cfm) — is redirected back toward that corner in the two 85/15 cases. In the sump cut, the off-curtain corner is not improved compared with the conventional simulation cases (Fig. 6a): the gas level at the gas 2 monitor drops a little from 7.38 ppm to 7.26 ppm in the experimental data and from 6.41 ppm to 6.28 ppm in the CFD simulation. Also, CFD simulation revealed a phenomenon not evident in the experimental data. In Fig. 7, a potential large and high gas cloud is located on the right above the cutting drum. In the slab cut (Fig. 6b), the off-curtain corner gas levels are improved: the gas level at the gas 2 monitor falls from 7.38 ppm to 0.86 ppm in the experimental data and from 6.41 ppm to 0.89 ppm in the CFD simulation.

For the two 50/50 cases in sump cut and slab cut, the gas concentrations are all higher in both continuous mining machine corners and within the duct (gas 3), and do not show any improvement compared with the conventional ventilation cases.

The 100 percent R case in the sump cut has high gas levels in the whole face regions, including the gas 1 to 3 gas monitor locations. In slab cut, the airflow sweeps the face well in the off-curtain corner, and there is low gas level in the duct, although the gas level at the curtain corner is a little higher than the conventional case.

Conclusions

In this slab cut study, it is observed that conventional scrubber ventilation clears most of the face regions 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 of 85/15 and 100 percent R redirecting scrubber exhaust flow back toward the face from the off-curtain side outlet can produce similar low gas ventilation effects. However, if their relatively higher gas results in sump cut is considered, these two configurations are not recommended for high gas mines.

In slab cut and sump cut, the evenly split 100 percent scrubber redirection cases did not show lower gas environments with the two discharge angles of 23° and 45° and are not recommended for highly gassy mines despite improvement in the slab cut study.

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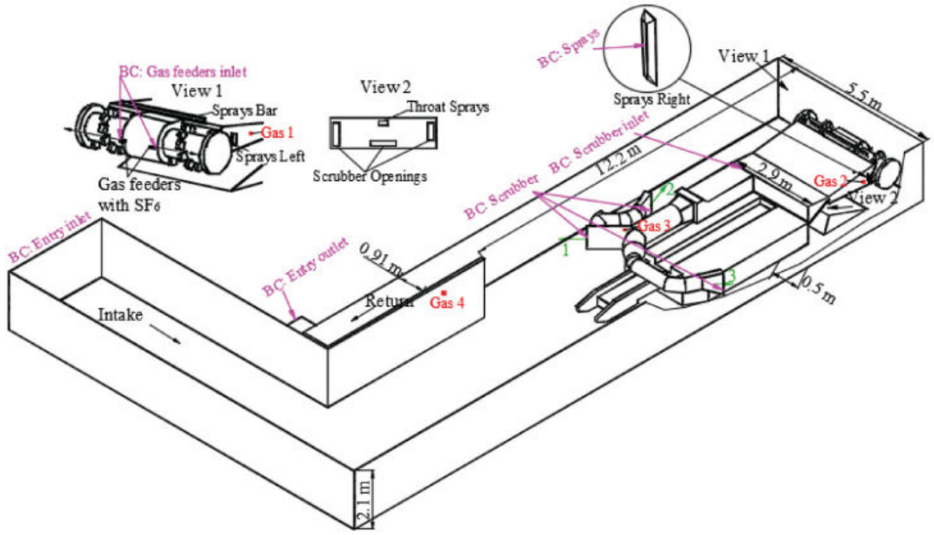

Figure 1.

Layout and dimension of the full-scale continuous mining machine gallery for scrubber redirection experiments in slab cut. Locations of boundary conditions (BC) are also shown.

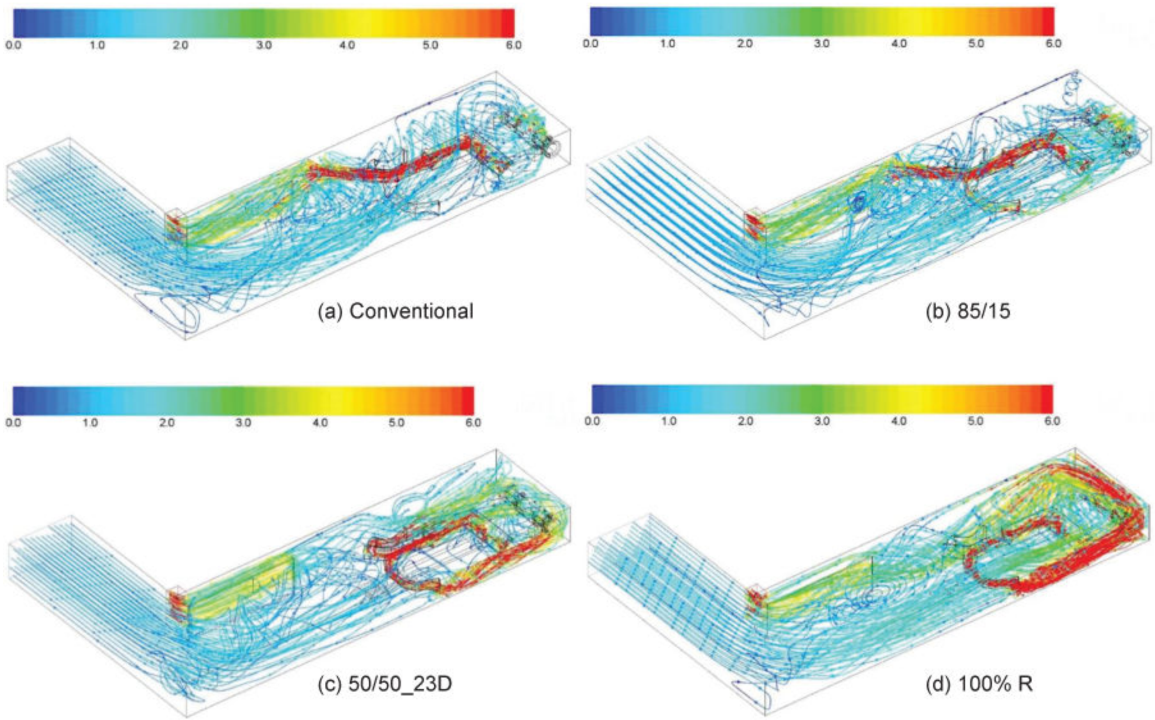

Figure 2.

Pathline of fresh airflow in slab cut for (a) conventional, (b) 85/15, (c) 50/50_23D and (d) 100 percent R. The different-colored arrow lines represent the velocities (0 to 6.0 m/s) of different particles released from the entry inlet.

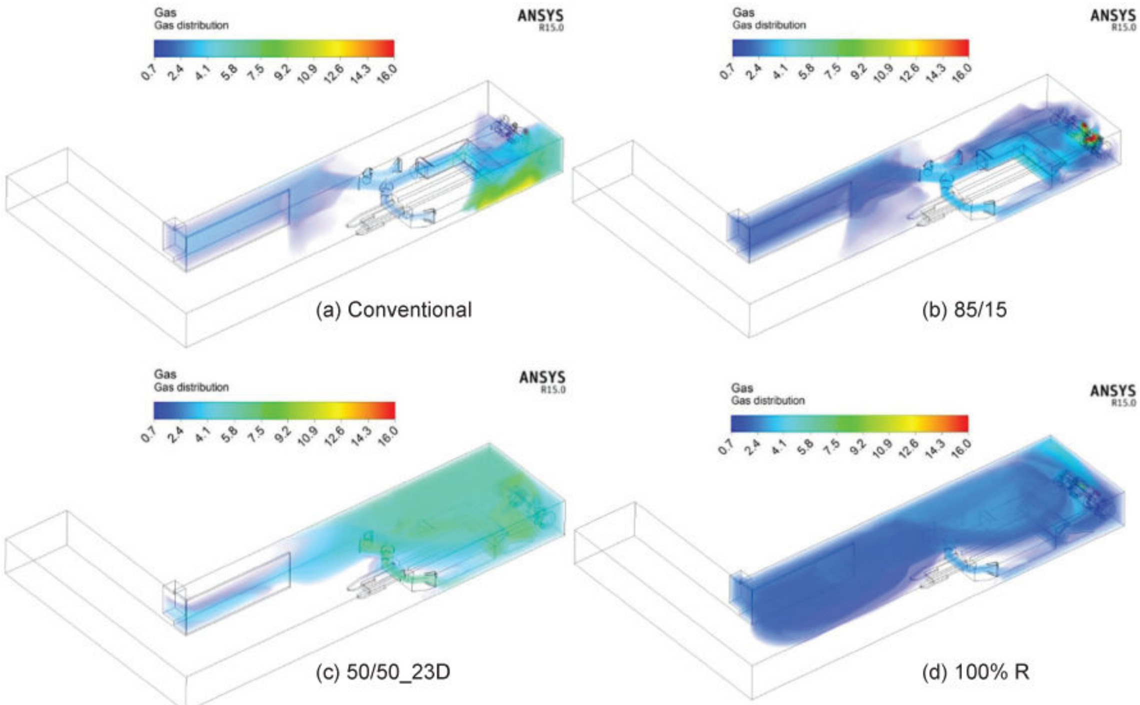

Figure 3.

Gas concentrations in slab cut for (a) conventional, (b) 85/15, (c) 50/50_23D and (d) 100 percent R. The different-colored regions represent different gas levels from 0.7 to 16.0 ppm.

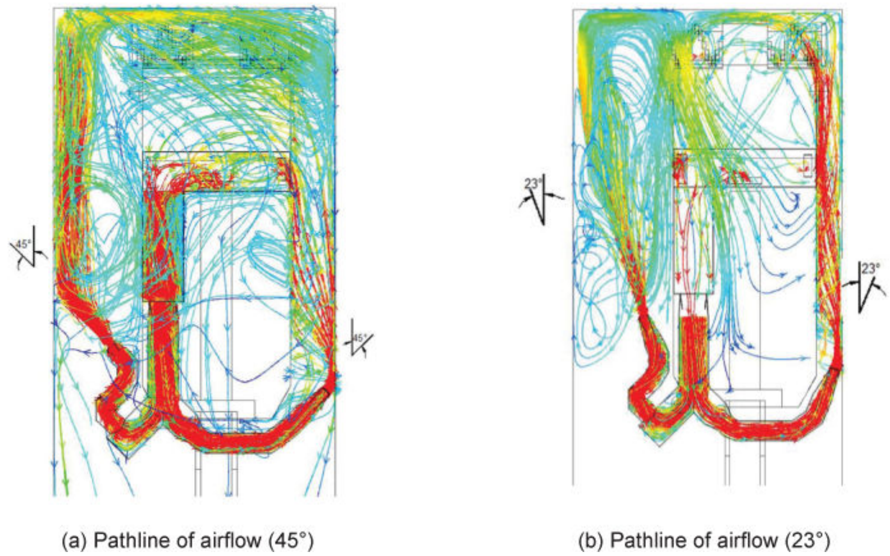

Figure 4.

Comparison of pathlines of airflows for (a) 45° and (b) 23° outlets (50/50) in slab cut.

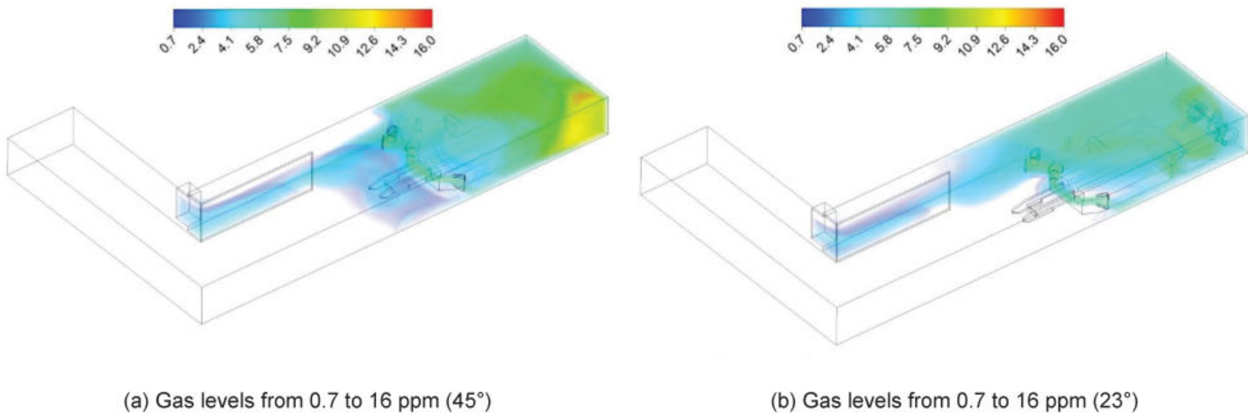

Figure 5.

Comparison of gas concentrations for (a) 45° and (b) 23° outlets (50/50) in slab cut.

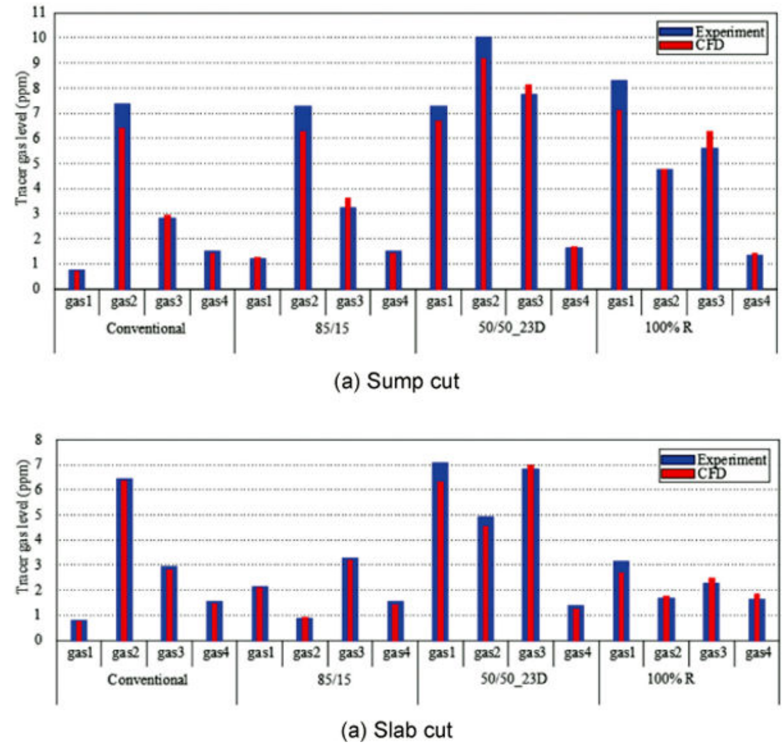

Figure 6.

Comparison of experimental data with CFD at the four sampling locations, gas 1 to 4, in (a) sump cut and (b) slab cut.

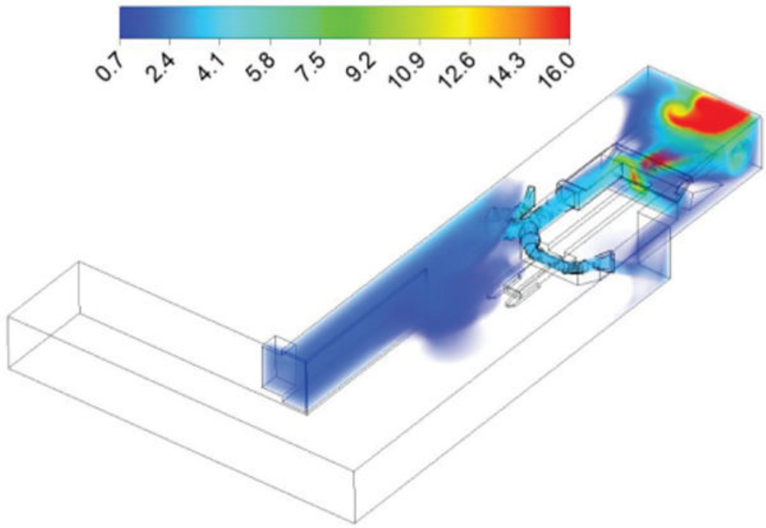

Figure 7.
Gas concentrations for simulation of 15 percent scrubber redirection and 85 percent conventional scrubber discharge in sump cut. The regions represent gas levels from 0.7 to 16.0 ppm (Zheng et al., 2015).

Table 1

Percent difference (Diff.) between experiment (Exp.) and CFD simulation (CFD) in slab cut for the four SF_6 monitors, gas 1–4, located as shown in Fig. 1.

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

Table 2

Predictions of gas levels for 50/50_45D and comparison with 50/50_23D, for the four SF_6 monitors, gas 1–4.

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