How Scrubbers Help Ventilate the Face During Deep Cut Mining with a Blowing Curtain

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ABSTRACT: In the Department of Mining Engineering at the University of Kentucky a comprehensive validation study of current Computational Fluid Dynamics (CFD) tools against mining-related benchmark experiments has been conducted. A wide array of ventilation schemes and mining configurations has been considered. In this paper, the authors will present, compare, and discuss the experimental and numerical data collected during the part of the study dedicated to the effect of machine-mounted dust scrubber on the performance of a face ventilation system for deep cut mining. These scrubbers, whose primary purpose is dust collection, have been shown to be very useful ventilation devices in directing air into the immediate face area where ventilation is poor during the box cut mining sequence. Based on studies carried out by the former U.S. Bureau of Mines, NIOSH, MSHA and industry, the recommended ratio between the scrubber airflow $\mathbf{Q_s}$ and the ventilation airflow $\mathbf{Q_{in}}$, should be equal to one. The authors will demonstrate and discuss the flow behaviors in the face area for the different values of the $\mathbf{Q_s/Q_{in}}$ ratios.

1 BACKGROUND

During the past twenty years, since the advent of remote controlled continuous miners and deep cut (extended advance) for room and pillar mining operations (Wellman, 1981), the safety and productivity of mining operations has increased significantly. However, this high production presents environmental problems in that, per unit time, more dust is generated and higher levels of methane are liberated at the face during coal extraction. These conditions require the supply of more air into the face of the excavated entry for safe dilution. One of the ventilation techniques being used in conjunction with this modern mining method (Goodman et al., 1990) is the blowing curtain in conjunction with a machine-mounted dust scrubber. Implementation of this technique has a significant influence on the airflow patterns in the entry working area and the design of their air handling capacities.

The former U.S. Bureau of Mines (currently NIOSH), Mine Safety and Health Administration, and the coal industry have conducted significant studies to evaluate the performance of face ventilation systems through the use of full scale tests (underground/surface) or scaled physical modeling. These studies led to recommendations that make these systems more effective. However, because of the aerodynamic complexity in the face area due to the variety of ventilation arrangements and the limitations of the experimental methods, some doubts still exist when evaluating the effectiveness of such a system.

The design of a balanced ventilation system for the above-described scenarios requires considering the system in three rather than two dimensions. With Computational Fluid Dynamics (CFD) many design alternatives can be explored in a relatively short period, and detailed three-dimensional results can be viewed graphically. This graphical type of information concerning airflow, gas, and dust distribution established by CFD are readily rationalized, and could lead to confidence in the final design of a mine face ventilation system. However, to develop this confidence, extensive validation studies are required involving comparisons between physical and numerical (CFD) modeling (Hargreaves and Lownsdes, 2001).

2 INTRODUCTION

During the last three years a validation study, funded by NIOSH Grant # R01 CCR415822, has been carried out in the Department of Mining Engineering at the University of Kentucky. The goal of this study was to prove a CFD code's ability to predict, evaluate, and design effective face ventilation systems. To achieve this goal the authors performed the following tasks:

- Designed and built a scaled physical model of selected face ventilation systems (see Wala et al., 2003),
- Performed a series of measurements using Particle Image Velocimetry (PIV) (Turner et al., 2002), to determine the velocity fields in the model,
- Developed three-dimensional numerical models of the tested systems and performed computer simulations using numerous CFD codes, and
- Compared experimental and numerical data for the purpose of CFD code validation.

One of the scenarios being tested for validation purposes was to ventilate equipment-free entry for cutting depth of approximately 18.3 m (60 ft). According to the mining plane this 18.3 m (60 ft) deep cut should be completed in a four 9.2 m (30 ft) cuts (passes), using blowing curtain ventilation system, see Figure 1. The results from the simulation study, using a scaled physical model, are shown in Figures 2, 3, 4 and 5 (Wala et al., 2000, 2002 and 2003). These figures increased an understanding of the flow behavior in cases of mining a deep cut using a blowing curtain for ventilation.

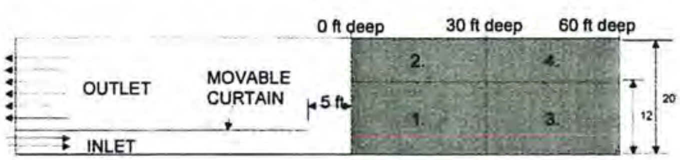

Figure 1. Test section geometry and the scenarios examined.

The major characteristic of the flow pattern, specifically for the box cutting sequence, is that 70 to 80% of the air leaving the end of the blowing curtain almost immediately separates from the rib and as a primary flow turns back toward the return. This separation is driven by an adverse pressure gradient which builds up as the width of the entry decreases. The rest of the curtain's airflow, approximately 20 to 30%, called the secondary flow, continues to flow toward the immediate face area in the opposite direction. As can be seen in general, the ventilation air delivered by the blowing curtain does not flow into the immediate face area.

Figure 2. PIV velocity magnitude and vectors for a 30 ft deep cut with a slab.

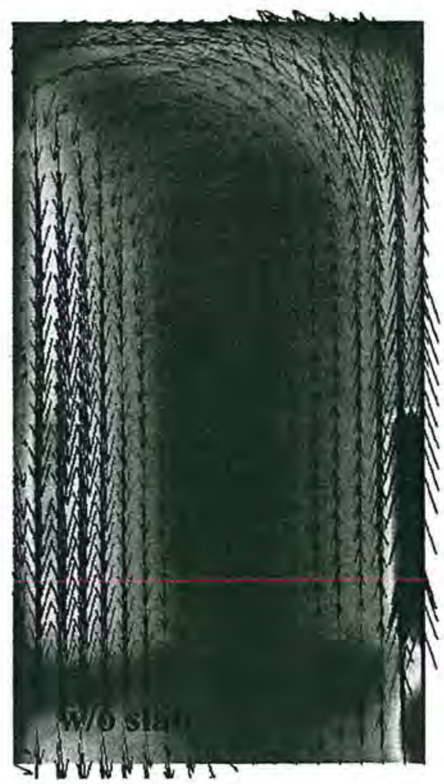

Figure 3. PIV velocity magnitude and vectors for a 30 ft deep cut without a slab.

During the validation studies the authors tested over a hundred scenarios for different combinations of such parameters as curtain setback, intake air quantity delivered by the curtain, tight-rib distance (curtain distance from the rib), and mining sequence. The data collected during these studies allows direct conclusions concerning the flow behavior.

The authors presumed that, until that time, the flow patterns for these mining scenarios had not been fully understood because of limited opportunity to monitor the flow patterns during full-scale experimental studies performed underground or on the surface. The only sources of information found by authors concerning the similar flow behavior as shown in Figures 2-5 were recognized and described by Luxner (1969) and Taylor et al., (1997).

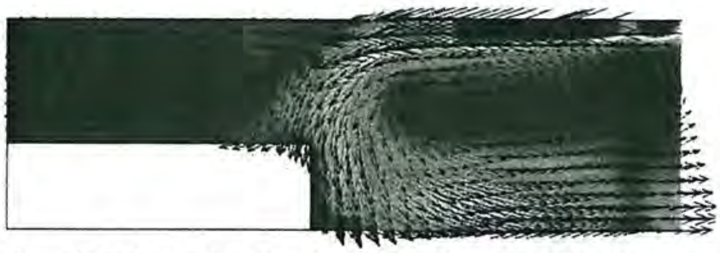

Figure 4. PIV velocity magnitude and vectors for a 60 ft deep cut with a slab.

Figure 5. PIV velocity magnitude and vectors for a 60 ft deep cut without a slab.

To ensure that scaled model test results interpret conditions reliably in the underground face area the cooperative validation testing has been performed by the Mining Engineering Department, University of Kentucky and NIOSH, using full-scale testing gallery at the NIOSH Pittsburgh Research Center. These studies proved that a 1:15 scaled laboratory model used for the project is a valid tool and realistically simulated underground conditions for the face ventilation systems. Observation showed the flow patterns for one of the scenario tested using laboratory scaled model and at the full-scale model as very similar, including recirculation.

As mentioned before, since remote controlled continuous miners were introduced, deep cut mining was an opportunity for mine operators to increase productivity. However, the presence of airborne coal dust in the face area was a major obstruction. This coal dust can cause poor visibility around the cutting head and can expose the miners to high levels of respirable dust. A practical means of removing this dust is with a dust-collecting scrubber mounted directly on the mining machine (U.S. Bureau of Mines, 1983). When the scrubbers were added to the face ventilation system of coal mines, the existing arrangements of the face ventilation systems were altered to accommodate these scrubbers.

Many studies concerning face ventilation with scrubbers were carried out in the United States in the last twenty years. The authors would like to mention some of them, which have contributed greatly to this topic; Gillies (1982), Clouse (1982), Volkwein and Thimons (1985), Jayaraman et al. (1992), Taylor et al. (1997), Thimons et a1. (1999), Kissell (2003). Most of the researchers, followed the Luxner comments concerning higher effectiveness of the blowing system versus the exhaust system, recommended the blowing curtain as the best suited ventilation system for scrubber applications, particularly because the free jet of high initial momentum leaving the end of the line curtain should penetrate into the immediate face area sweep the face and flow into the return.

This is true, according to Figures 2-5, as long as the entry width is more than 16 foot, as was discovered during this study (Wala et al., 2003). This means that only during the slab cutting scenario does the advantage of the blowing curtain prevail. For the rest of the mining scenarios the ventilation air does not like to flow to the immediate face area where it is mostly needed in the gassy mines for methane dilution.

The effects of the machine-mounted scrubber system on levels of methane and respirable dust were tested first by Ingersoll Rand Research Inc., (Clouse, 1982). These studies have shown that properly designed machine–mounted scrubber systems can allow curtain setbacks of 12.2 m (40 ft), while still controlling respirable dust and methane levels. At the same time, the machine-mounted scrubber, whose primary role was to collect respirable dust at the face (dust source location), was found to be also an air-moving device (ventilation device).

Based on the Ingersoll Rand studies, MSHA recommended a ratio between the scrubber flow $\mathbf{Q_s}$ and the intake flow $\mathbf{Q_{in}}$ of close to one. A study performed by Jayaraman, 1992, supports these finding, however, latest studies performed by Taylor at el., 1997 and by Thimons at el., 1999 show that the relations between face ventilation performance and scrubber/ventilation flow ratios are more complicated than was previously thought.

The authors, based on the results from the experimental studies using physical and numerical modeling, will demonstrate and discuss the flow behavior in the face area for the varied $\mathbf{Q_s/Q_{in}}$ ratios.

3 EXPERIMENTAL STUDIES

In order to study the effect of the scrubber on the face ventilation system, a scaled physical model of such a system was constructed in the Ventilation Laboratory at the Mining Engineering Department, University of Kentucky.

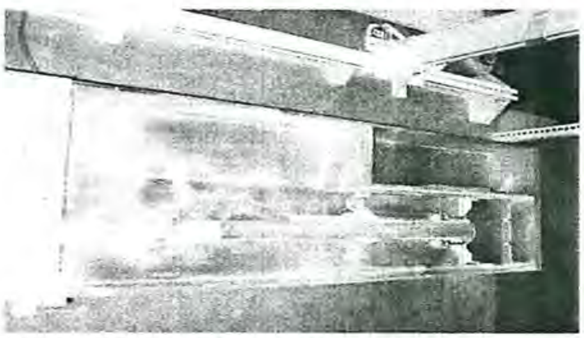

Figure 6. Simplified scrubber model in test section.

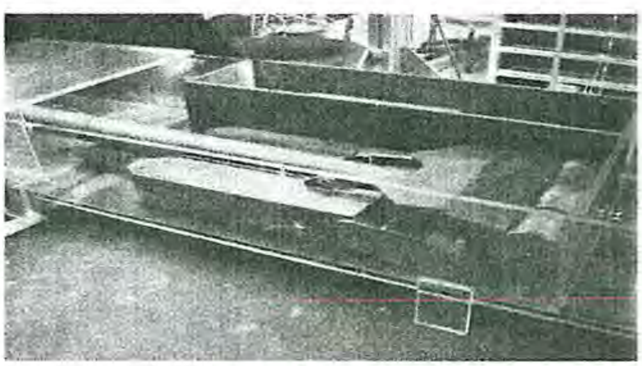

Figure 7. Machine mounted scrubber model in test section.

3.1 Description of the Physical Model

3.1.1 Entry Model with Fans

The analysis of face airflow patterns was undertaken using 1:15 physically scaled model. This scaled model of a typical underground room and pillar coal mine with an entry of 2.1 m (7 ft) high and 6.1 m (20 ft) wide was designed and built out of transparent Plexiglas. Scaling of the entry flow rate was performed using dimensional analysis based on the Reynolds Number, $Re=UL/\nu$, where U and L are the velocity at the brattice line mouth and width of the inflow (distance between the brattice line and entry rib), respectively. The model consists of three significant parts:

- The working section, which represents a face area, where movable Plexiglas walls can be used to replicate many different ventilation configurations such as box-cut or slab-cut arrangements with brattice setback distances varying from zero to 18.3 m (60 ft).
- The middle section, which represents an ordinary mining entry with a partition (brattice line/curtain), divides the entry into a narrow 0.6 m (2 ft) wide intake and an 5.5 m (18 ft) wide return airways.
- The intake/return section, where the ventilation system can be arranged as either blowing or exhausting by changing the fan location.

The primary airflow through the entry was drawn by a main fan in series with a smaller axial speed controllable auxiliary fan. The maximum available airflow induced through the model corresponds to the 3.0 m^3/s (6,500 CFM) for the underground conditions.

3.1.2 Scrubber Model

The scrubber system for this modeling study did not exactly simulate the underground scrubber arrangements. Since the scrubber system could not be modeled exactly as it appears in a mine due to limited space, a simplified model of the scrubber was simulated using open ended 2 inch diameter PVC pipe. The airflow though this pipe was drawn by a suction system. The maximum airflow induced by the scrubber system corresponds to 1.4 m^3/s (3,000 CFM) for the underground conditions.

For validation purposes two different arrangements with the scrubber were tested. First, as shown in Figure 6, a cylindrical "scrubber" was simulated by the straight PVC pipe placed in the middle on the entry floor, 1.5 m (5 ft) from the face. Second, as shown in Figure 7, the same PVC pipe was placed on the top of a continuous miner model, corresponding to the Joy Model 14CM Continuous Miner, located in the face area.

The model was arranged to simulate two critical ventilation scenarios as follows:

- SCENARIO #1
  The end of the box cut during the first mining pass (sequence), with a setback distance being 10.6 m (35 ft) (see Figure 1).
- SCENARIO #2
  The end of the box cut during the third mining pass (sequence), with a setback distance being 18.3 m (60 ft) (see Figure 1).

3.2 Particle Image Velocimetry (PIV)

PIV was used to measure instantaneous velocity fields of the time dependent flows in this scaled model. PIV is a non-intrusive, optical technique for the measurement of planar flow velocities. The technique measures the velocity of a fluid indirectly by means of the measurement of the velocity of tracer particles within the flow. A plane of the flow is illuminated twice within a short time interval, and the images of the illuminated particles are digitally recorded on two separate image frames of a CCD camera (Turner et al., 2002). Fourier analysis is used to extract the planar particle velocity information from the image pairs. The experimental set-up of the PIV measurement system consists of four sub-systems: (1) Seeding, (2) Illumination, (3) Recording, and (4) Evaluation. The integrated PIV system used in this study is comprised of the following components: (1) laser and light sheet optics, (2) image recording system, (3) synchronizer, (4) particle generator, and (5) image analysis and display, (Turner et at., 2002).

4 RESULTS AND DISCUSSION

4.1 Experimental Data from Scale Modeling

Based on the results collected during the flow distribution study in the equipment-free entry, shown in Figures 2-5, it was found that the worst ventilation conditions occur during the box cutting sequences (see Figures 2 and 4). Using the physical model of the face ventilation system, these two critical ventilation scenarios, described above, represent possible mining arrangements for a 18.3 m (60 ft) deep cut in four passes.

The performance of the face ventilation for theses two extended cut mining scenarios was a goal for this validation study. The geometry of the entry examined was 2.1m (7 ft) high and 6.1 m (20 ft) wide. The maximum intake air in volume of 3.0 m^3/s (6,500 CFM) was provided to the face area by means of a blowing curtain.

Figures 10 and 11 show the flow streamlines from PIV measurements at the horizontal middle plane of the model for SCENARIO #1 and SCENARIO #2, with and without the scrubber, respectively. As previously mentioned, the scrubber for this particular case was simulated as a simple pipe located on the floor of the empty entry. The general observation from these two tests are that scrubbers help to bring the air into the immediate face area during the box cut mining sequences, whereas it would not penetrate to the face otherwise. This makes the 18.8 m (60 ft) deep cut mining possible.

We were also interested in determining the relationship between the performance of the face ventilation system and the flow ratio between the intake and scrubber flows. Figures 8a, 8b, and 8c show the flow streamlines at the horizontal middle plane of the entry for three different flows ratios Q_s/Q_{in} of 0.14, 0.34, and 0.53, respectively. From a methane removal point of view for this equipment empty entry scenario, the eddies indicate poor ventilation of the face due to excessive recirculation.

Figures 9a, and 9b shows similar flow streamlines as shown in Figure 8b and 8c, except during these tests the continuous miner model was present in the face area. The measurements were taken at the horizontal plane above the miner. By comparing these figures it can be seen that equipment present in the face creates additional obstructions to the flow and decreases the effectiveness of the ventilation system.

4.2 Numerical Modeling

The numerical simulation for these two scenarios described above was performed using CFX commercial CFD (Computational Fluid Dynamics) software package. Based on the intensive validation studies performed as a part of the entire project, the CFX software package along with the SST (Shear Stress Transport) turbulence model was selected for its ability to accurately predict separation due to adverse pressure gradients, as opposed to the k-ε model.

PIV results from the experimental studies of SCENARIO #1 with the cylindrical scrubber (Figures 6) and continuous miner with on-board mounted scrubber (Figure 7), served as a baseline for the numerical simulation validation. In these studies, the scrubber mass flow ratio was normalized by the mass flow at the intake flow (behind the curtain). Thus, the results presented in Figures 14 illustrate predicted flow fields for the cylindrical scrubber at the scrubber flow ratios of 0.2, 0.3, 0.4, 0.7 and 1.0, respectively. The boundary condition for the scrubber is set as a constant velocity outlet which is released outside the original geometry. These boundary conditions were set on the scaled model during the experimentations. The grid density was based on the coarse grids tested for the previous simulation exercises.

4.3 Discussion

In comparing the numerical (CFD) results with the experimental (PIV) results, one will see good similarity in the flow behavior in the face area. However, some flow pattern discrepancies can be noticed. The experimental results show the location of the separation point to be more sensitive to smaller values of the scrubber mass flow ratio. This flow behavior could be explained by existence of the unsteady flow along the wall (rib). However, once the scrubber mass flow ratio reaches a level near 1.0 the separation is removed and the flow carries to the immediate face area. This is notable since most scrubbers in actual mining applications are required to have a mass flow ratio equivalent to 1.0. Also, it can be seen that as the flow ratio approaches one the recirculation (eddies) in the immediate face area increased.

Figure 11 show simulated 3-D flow streamlines in the face area when a simplified virtual continuous miner with scrubber was inserted into the entry for the 9.1 m (30 ft) box cut scenario. The miner was equipped with a virtual scrubber which is incorporated into the geometry of the mine such that the scrubber's inlets are placed on each side of the miner and the exhaust is placed at its rear. Unlike the previous scrubber, this scrubber was modeled with the "fan" UDF (User Defined Function). This method of modeling allows the user to put a pressure gradient condition on a plane within the scrubber's duct essentially modeling a blower mounted to the miner. The main difference between this method and the previously used method is that the scrubber's exhaust is released within the mine as opposed to outside. This better represents the scenario of a miner with on-board scrubber and would be very difficult for an experimentalist to implement into a scaled model due to flow restrictions on fans small enough to fit these scaled geometries. Figure XX illustrates the resulting flow over the miner without the use of a scrubber. The effect of the scrubber can clearly be seen by comparing Figures 2-5 with Figures 8-11.

5 CONCLUSIONS

- These scrubbers were shown to be very useful tools in moving air into the immediate face area where ventilation is poor, especially during the box cutting sequences.
- Scrubbers introduced as dust collection devices help to bring the air to the immediate face area and should be termed face ventilation devices, as well. Without a dust scrubber, the blowing curtain is ineffective for controlling respirable dust and methane as can be seen from Figures 2, 3, and 4.
- With scrubbers, more efficient ventilation can be obtained in the face areas without the need for miners to extend ventilation controls inby permanent roof supports.
- The flow ratio between intake and scrubber is an extremely important factor, which could be controlled for optimization of the face ventilation system.

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Figure 8b. Streamlines from PIV measurements with the simplified scrubber model for a 35 ft setback with a slab; Q_s/Q_{in}=0.34.

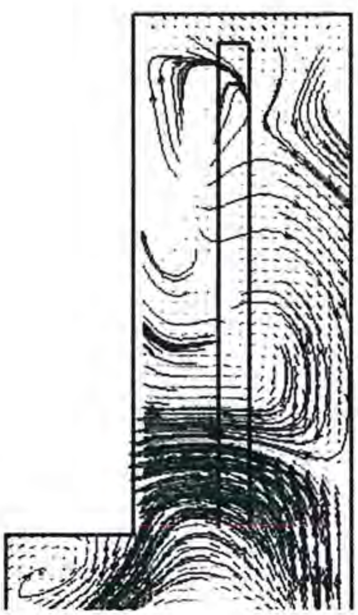

Figure 8a. Streamlines from PIV measurements with the simplified scrubber model for a 35 ft setback with a slab. (a) Q_s/Q_{in} of 0.14.

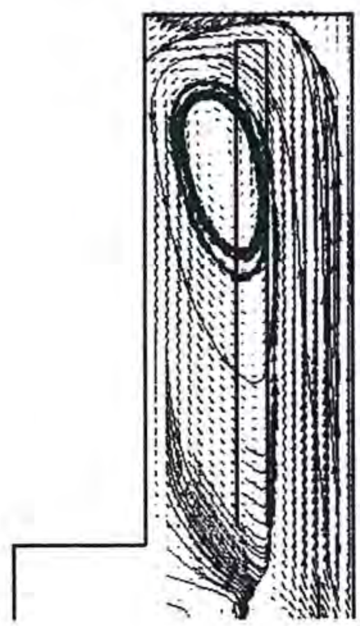

Figure 8c. Streamlines from PIV measurements with the simplified scrubber model for a 35 ft setback with a slab.; Q_s/Q_{in}= 0.53.

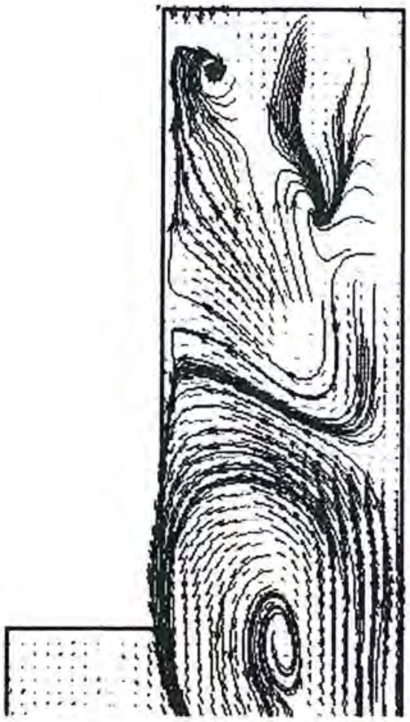

Figure 9a. Streamlines from PIV measurements with the machine mounted scrubber model for a 35 ft setback with a slab; $Q_s/Q_{in}= 0.30$.

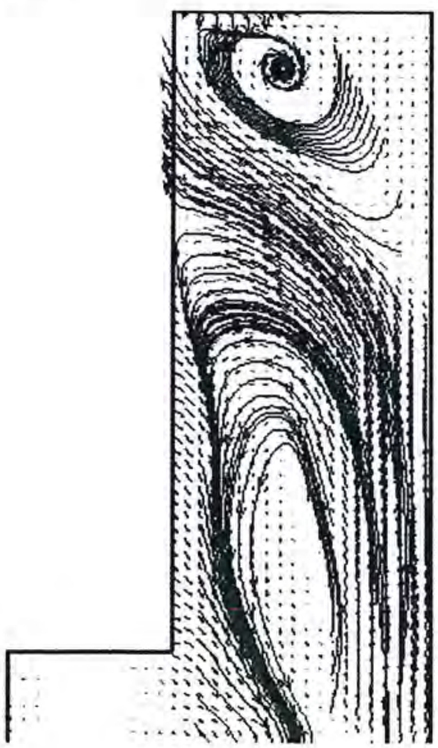

Figure 9b. Streamlines from PIV measurements with the machine mounted scrubber model for a 35 ft setback with a slab; $Q_s/Q_{in}= 0.53$.

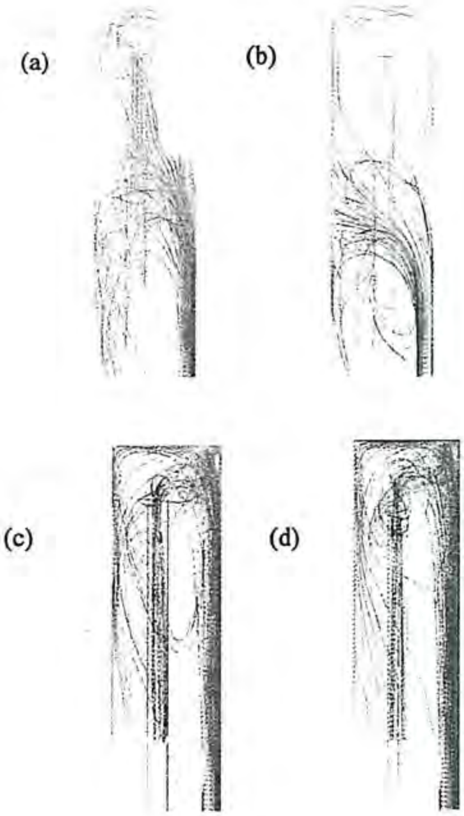

Figure 10a, 10b, 10c, 10d. CFD results for a 30ft deep cut with a simplified scrubber model for a 35 ft setback; (a) $Q_s/Q_{in}=$ 0.20; (b) $Q_s/Q_{in}= 0.40$; (c) $Q_s/Q_{in}= 0.70$; (d) $Q_s/Q_{in}= 1.0$.

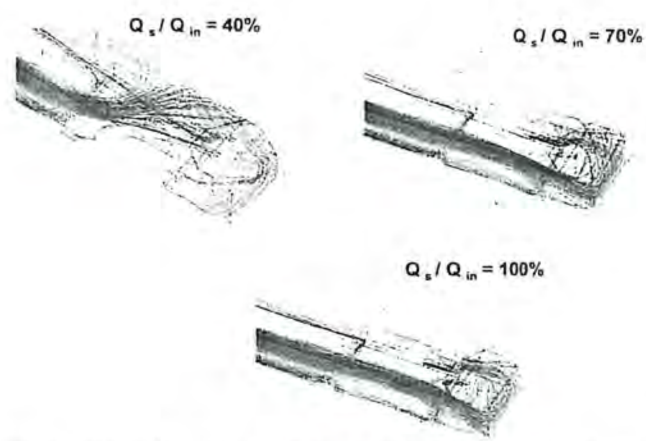

Figure 11a, 11b, 11c. CFD results for a 30ft deep cut with a machine mounted scrubber model; (a) $Q_s/Q_{in}= 0.40$; (b) $Q_s/Q_{in}=$ 0.70; (c) $Q_s/Q_{in}= 1.0$.