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LAB EVALUATION OF A NEW TYPE OF AIR-CLEANING FAN FOR RESPIRABLE DUST CONTROL

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ABSTRACT

Researchers at the National Institute for Occupational Safety and Health (NIOSH) performed a series of lab tests to evaluate the respirable dust removal capacity of an industrial air-cleaning fan. Limestone and coal dust were tested separately in NIOSH's full-scale drill table simulator at the Pittsburgh Mining Research Division (PMRD). Gravimetric samplers with Dorr-Oliver Cyclones and 37-mm filters were used at two upstream and four downstream locations inside and outside of the drill shroud chamber. There were six tests performed for both the limestone and coal dust experiments. In the limestone tests, an average respirable dust concentration of 98.86 mg/m^3 was achieved upstream of the air-cleaning fan. The filter results show that the averaged respirable limestone dust reductions were 7.84%, 8.81%, 10.94%, and 18.02% at the four sampling locations downstream of the fan. In the coal tests, upstream samplers achieved an average of 129.03 mg/m^3 of respirable coal dust. The averaged dust reductions were 9.54%, 9.83%, 18.54%, and 19.21% at the four downstream sampling points. The results indicate limited cost benefits of using this technology because of the relatively low dust reductions determined from this laboratory study.

INTRODUCTION

Mining and mineral processing can produce large amounts of dust by drilling, blasting, excavating, hauling, crushing, dumping, screening, and more work processes. This can potentially expose workers to elevated dust levels that may result in Coal Workers' Pneumoconiosis (CWP) and silicosis. Medical treatment cannot cure these diseases, so prevention through dust control is essential. To protect workers, federal regulations limit their respirable dust exposure and require engineering controls in an effort to reduce dust generation from contaminating the working areas.

For metal/nonmetal mines, the United States Mine Safety and Health Administration (MSHA) has adopted the threshold limit values recommended by the American Conference of Governmental Industrial Hygienists [1-3]. The total airborne dust standard is 10 mg/m^3. However, if the sample contains greater than 1% crystalline silica, a respirable dust threshold limit value (TLV) is calculated with equation 1 [4]:

$$\text{Respirable dust TLV} = \frac{10\ mg/m^3}{(\%Q)+2(\%C)+2(\%T)+2} \quad (1)$$

Where Q, C, and T represent quartz, cristobalite, and tridymite forms of respirable crystalline silica, respectively. Quartz is the most common form of respirable crystalline silica and is commonly found in samples analyzed from mining sites. Cristobalite and tridymite are more hazardous forms of crystalline silica and are limited to 50% of the value calculated from the formula for quartz.

For coal mines, the current MSHA regulation for permissible dust exposure for mine workers is 1.5 mg/m^3 of airborne respirable coal mine dust for full shift sampling [5]. If the sample contains more than 5% quartz, a respirable dust standard is calculated with equation 2 [6]:

$$\text{Respirable dust standard} = \frac{10\ mg/m^3}{\%\ respirable\ quartz} \quad (2)$$

Equations 1 and 2 regulate the exposure limit for respirable quartz to a maximum 0.1 mg/m^3 for all workers in metal/nonmetal and coal mines. The maximum exposure limit for respirable cristobalite and tridymite is 0.05 mg/m^3 for metal/nonmetal mines.

Despite the efforts in controlling respirable dust through regulations and engineering controls, CWP cases are still prevalent and have been increasing from the early 2000s [7]. An x-ray surveillance study recently completed under the NIOSH Enhanced Coal Workers' Health Surveillance Program (ECWHSP), which offered free chest radiographs to surface coal miners in 16 states, revealed that pneumoconiosis (CWP and silicosis) was found among 2.0% of the 2,328 screened miners with at least 1 year of mining tenure. Twelve miners had radiographic changes consistent with progressive massive fibrosis, and 9 of these 12 miners reported no underground mining tenure [8].

The intent of this study is to continue the respirable dust control efforts through engineering solutions. A new air-cleaning fan was evaluated through laboratory testing. This fan device can be used as a standalone appliance to remove dust particles and to provide clean air for several applications in different environments including the electrical house, motor control center, mobile office unit, dragline excavator control room, hydraulic shovel excavator engine room, and others.

The fans are built to be able to separate dirt from air, using no filter element, bags, or other media. This eliminates most maintenance and saves energy because the fans no longer have clogged filters to service, replace, or reduce airflow rate. The design is intended to leverage the momentum of the dirt particles along with the advancing and rotating air to fling the particles out of the housing and return them back into the surrounding atmosphere through a dump shroud or a dump port. In addition, if extremely clean air is required, filters can be installed downstream of the fan to filter the small mass of remaining particles.

The National Institute for Occupational Safety and Health (NIOSH), Pittsburgh Mining Research Division (PMRD) obtained a fan to conduct lab tests to determine the viability of such a device and to determine applications for use in mining. This study documents the complete evaluation process.

EXPERIMENTAL DESIGN

Test facility

The NIOSH full-scale drill simulator laboratory was utilized to evaluate the respirable dust removal by the air-cleaning fan as shown in Figure 1. The drill simulator room (outer chamber) has a total volume of 27.24 m^3 (960 ft^3) with 3.66-m (12-ft) in width, 3.05-m (10-ft) in depth, and 2.44-m (8-ft) in height. The drill shroud (inner chamber), located in the center of the outer chamber, measures 1.52-m wide by 1.22-m deep by 1.22-m high (5 × 4 × 4 ft.). The total volume of the inner chamber is 2.26 m^3 (80 ft^3). The laboratory has its own dust feeder and compressed air supply to provide a high dust concentration environment, an adjustable ventilation system by an exhaust fan, and a baghouse filtration system to filter the air and then to safely release it into the atmosphere. The detailed setup of the full-scale facility can be found in previous literature [9-11]. The facility was modified according to the requirements of the air-cleaning fan evaluation.

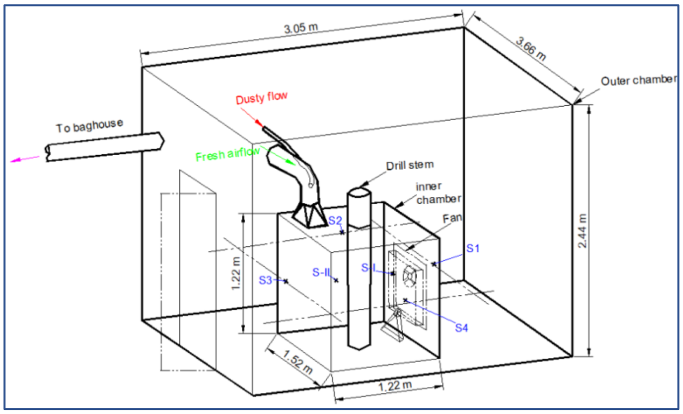

Figure 1. Modified setup for the respirable dust removal test of the air-cleaning fan at NIOSH's full-scale drill table simulator.

As shown in Figure 1, the air-cleaning fan was installed on one side of the vertical deck shroud wall with the inlet opening at the inside of the inner chamber. The inner chamber was sealed at the bottom of the vertical plates to the floor. During the test, the air-cleaning fan drew fresh air directly from outside of the drill simulator room. On its way into the inner chamber, dusty flow from the dust feeder system was delivered by compressed air and mixed with the fresh airflow. The dusty flow was then further mixed inside the inner chamber and went through the air-cleaning fan. Dust particles were then separated from the main air stream and dumped through a duct at the bottom of the fan to the floor at the inlet side. Exhaust air was then drawn by the ventilation system to the baghouse, where it was further filtered before releasing into the atmosphere.

At the power required by the air-cleaning fan (460 Volts / 60 Hz / 3 Phase), the fan has an airflow capacity of about 600 cfm (0.28 m^3/s). The ventilation system of the drill table simulator has a flow capacity of 1,000 cfm (0.47 m^3/s) and can be adjusted to match a lower flow rate to make sure the simulator room was not pressurized or depressurized to affect the performance of the air-cleaning fan.

To test the air-cleaning fan for respirable dust control effects, as shown in Figure 1, there are six sampling packages used in the test (four outside and two inside of the inner chamber):

1) One sampling package at the inlet opening of the air-cleaning fan (S-I in Figure 1);
2) One sampling package downstream of the fresh airflow duct (S-II in Figure 1);
3) Four sampling packages, stationed outside at each side of the inner chamber (S1 – S4 in Figure 1). The height of the four outside samplers was determined by S1, which was put in the exhaust flow from the air-cleaning fan with the bottom of the sampling rack 4 ft. (1.22 m) above ground.

Sampling method

Gravimetric and instantaneous samplers were used to test the air-cleaning fan for respirable dust reduction evaluation. A typical sampling package includes one instantaneous sampler and two gravimetric samplers, as shown in Figure 2. The gravimetric sampler is the coal mine personal dust sampling unit (CMPDSU) consisting of an Escort Elf pump, a 10-mm Dorr-Oliver cyclone, and a 37-mm PVC filter. The permissible sampling pumps were calibrated at 2 L/min for coal or 1.7 L/min for limestone before the study. All filters were pre- and post-weighed at the weighing lab, and respirable dust concentrations were calculated for the time-weighted-average (TWA) concentration of the test duration. These concentrations are calculated as in equation 3 below to determine the respirable dust removal capability of the air-cleaning fan.

Figure 2. A sampling package consisting of a pDR-1000 and two gravimetric samplers used in the air-cleaning fan evaluation test.

$$\text{Respirable dust concentration (mg/m}^3\text{)} = \frac{Mass \times 1000}{Flowrate \times Sample\ time} \quad (3)$$

Where

Mass	=	Mass of sample on 37-mm filter (mg)
Flow rate	=	Flow rate of air through the Escort ELF pump, generally set to 2.0 L/min for coal dust and 1.7 L/min for limestone dust
Sample time	=	Length of sampling period (minutes)

The instantaneous sampler was the Thermo Fisher Scientific pDR-1000. This instantaneous sampler uses light-scattering technology to measure dust in the range ≤10 μm in aerodynamic diameter and has the capability to record relative dust concentration measurements. The pDRs have a user-defined sampling interval which was set for 15-second intervals during the test to detect whether there were any problems during the tests. Later, the recorded dust measurements were used to provide the accurate sampling time period used in equation 3.

Experimental cases

Two types of dust were tested to make the evaluation: limestone and coal dust. All other parameters of the testing were held constant to ensure that testing proceeded consistently for all the tests. They include dust feeder operating speed, compressed air pressure, stable ventilation in the simulator room, and constant flow rate by the air-cleaning fan. Six tests were performed for both the limestone and coal dust experiments.

Test procedure

In the beginning of the test day, the pDR-1000 was zeroed to ensure maximum accuracy on concentration measurements. Before testing began, the ventilation rate inside the duct to the baghouse (Figure 1) was measured to make sure it met the requirement of 600 cfm (0.28 m^3/s) to discharge the flow from the air-cleaning fan.

Before each test, the numbers on the pDR, filter, Escort Elf pump, the sampling rack, and the sampling location for each sampling package were all recorded to make sure the dust concentration data obtained from each test could be correctly tracked. Then, the pDR, Escort Elf pump, and the dust feeder with compressed air was started at predetermined settings and operated through the testing period. After each test, the filters were replaced with new ones, and the pDR data was downloaded to a lab computer. After each day's test, the ventilation rate for the simulator room was checked again to make sure the ventilation system was operating properly.

Statistical analysis

Six independent experiments were conducted for both limestone and coal dust. Duplicate dust concentrations were measured for each location. The average of the duplicates was used for statistical analysis. The data were expressed as mean ± standard deviation (SD). The statistical differences were analyzed by one-way analysis of variance (ANOVA), followed by Dunnett multiple comparison test; $p < 0.05$ was considered statistically significant.

TEST RESULTS AND DATA ANALYSIS

Limestone dust test results

A pretest was performed with limestone dust for 45 minutes to determine if there were any problems with the facility upgrade and test design. It was also important to know whether 45 minutes was long enough to obtain a substantial amount of mass on the filter for analytical measurements. Based on the performance (50% dust feeder control speed and 80 psi of compressed air) and observation during the pretest, a 30-min testing period can get enough mass on the filter for further analysis. Therefore, the following tests were conducted in 30 min and repeated 5 times. Table 1 (see APPENDIX) shows the filter data for the limestone dust concentration at different sampling locations: S-I and S-II are inside the inner chamber and upstream of the fan, and S1-S4 are located outside the inner chamber and downstream of the air-cleaning fan. The pretest is titled as Test-1 45-min in the table. All the other tests (Test-2 – Test-6), including the six coal dust tests, are performed in 30 min.

For each test, the averaged dust concentration of the two filters at the same location is shown in the first line of the test in Table 1. Then, the second line shows a dust reduction rate of the samplers outside of the inner chamber S1-S4 compared to S-I, which is located at the immediate inlet of the air-cleaning fan. It can be observed from the table that the upstream respirable dust concentrations are in the range of 80–110 mg/m^3. This is achieved at 50% dust feeder control speed. At full momentum, it is estimated that the sealed drill shroud chamber can provide up to about a 200 mg/m^3 respirable limestone dust environment for future dust reduction product evaluation.

On the downstream side samplers, it can be observed that most of the dust concentration data are lower than the upstream ones. Dust reduction rates in Test-1, Test 3, Test-4, and Test-5 are in the range of 3.86%–27.12%, with the highest dust reduction rate (27.12%) at S3 in Test-4. Most dust reductions in these tests are in the range of 15%–27%. However, there are also negative dust reduction values in Test-2 and Test-6. Although these downstream values are only slightly above the upstream ones, they are still not neglectable. The reasons for these escalated dust levels may include: 1) compacting of the dust particles by packaging, transportation, storage, etc. These packed dusts may contain many respirable-size particles with a total size larger than the 50% cut-point of the cyclone (4 micron) in gravimetric samplers. The dust feeder and compressed air blow cannot break the bond of the particles. Therefore, the S-I sampler cannot pick the particles at the inlet side of the fan. However, once they are inside the air-cleaning fan, the high separation power of the fan throws these dusts against the inner side of the walls, releasing some of the respirable dust particles downstream of the fan. This process happened on all the tests, but in Test-2 and Test-6, this trend outran the particle removal effect. 2) Some systematic errors from the design of the experiment, limitations in the test facility, inaccuracy from the instrument and measurement, and other factors. All these known and unknown factors can affect the results in a favorable or an unfavorable way. Whether or not these downstream concentrations (S1–S4) are different from the upstream data (S-I), further data analysis may help to reveal if the differences are statistically significant. What needs the most attention is the dust concentration at S1. It is located directly at the outlet side of the fan.

Limestone dust data analysis

Table 2 shows the mean, standard deviation (SD), and coefficient of variation (CV) for limestone dust concentration at the sampling locations from six independent experiments. Duplicates of each location were used in each independent experiment. Generally speaking, a CV less than 10% means the data set is very good; a CV between 10% and 20% is good; a CV within 20%–30% is acceptable; and a CV greater than 30% may not be acceptable [12]. The low standard deviation and the CV value in Table 2 indicate the test results have less variance.

Figure 3 shows the decrease of respirable limestone dust concentrations at different locations. S-I was treated as a control group. Test results were expressed as mean ± SD. The statistical differences were analyzed by one-way analysis of variance (ANOVA), followed by the Dunnett multiple comparison test. $p<0.05$ was considered statistically significant. The limestone dust concentrations were reduced by 10.94% and 18.02% at S2 (89.06±10.68%, $p<0.05$) and at S3 (81.98±8.69%, $p<0.05$), respectively, while the limestone dust reductions at S1 and S4 were 8.81% and 7.84% and are not statistically significant ($p>0.05$). The dust level at the upstream S-II is 7.54% lower than that of the S-I, which means the dust was further mixed inside the inner chamber as it flowed toward the fan. However, it is not significantly different from the control group at S-I ($p>0.05$).

Table 2. The mean, SD, and CV for limestone dust concentration.

Location	**Mean** (mg/m^3)	**SD** (mg/m^3)	**CV (%)**
S-I	98.86	8.62	8.72
S-II	90.01	7.38	8.20
S1	88.59	8.15	9.21
S2	86.65	9.17	10.58
S3	79.92	9.19	11.50
S4	89.65	7.23	8.07

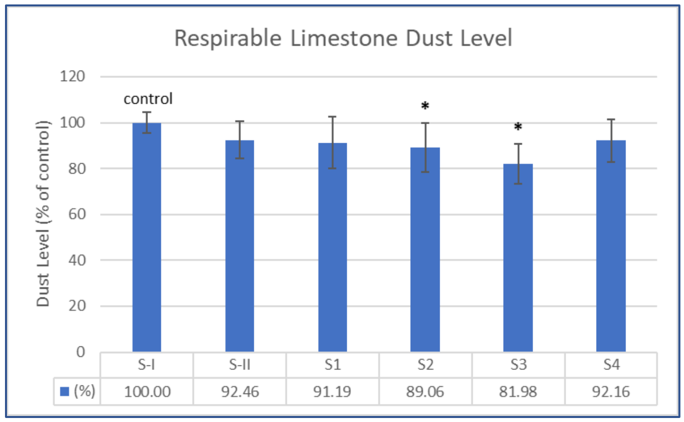

Figure 3. Respirable limestone dust reduction. Limestone dust concentrations were measured at six locations. Values are mean ± SD from six independent experiments. Duplicates of each location were used in each independent experiment. One-way ANOVA followed by the Dunnett posttest was used. Significance indicated by: * $p < 0.05$ vs. S-I control group.

The purpose of the study is to evaluate the respirable dust reduction capacity by the air-cleaning fan. From the test results, the downstream dust levels, on average, are all lower than the upstream ones. But the respirable dust concentration at the fan outlet S1 and downstream point S4 were not significantly different from that of the fan inlet point. At downstream points S2 and S3, the difference in the dust levels was statistically different. However, the average total respirable dust reduction rates are both still below 20%. If high respirable dust levels exist upstream of the air-cleaning fan, it may not provide a healthy environment downstream.

Coal dust test results

After the limestone dust tests, coal dust was used to evaluate the respirable coal dust reduction of the air-cleaning fan. Six 30-min tests were conducted with the same operation settings (50% dust feeder control speed and 80 psi of compressed air). Table 3 shows the averaged coal dust concentration data and dust reduction rate. The first line of each test shows the averaged coal dust concentration at the same sampling point. The second line shows the reduction rate of the samplers of S1-S4 compared to S-I.

It can be observed from Table 3 (see APPENDIX) that for the same 50% dust feeder setting, the feed coal dust contains a higher proportion of respirable-sized particles than the limestone dust. The upstream dust levels at S-I and S-II are in the range of 90-160 mg/m^3. At full dust feeder control speed, it is estimated that the inner chamber can provide up to a 300 mg/m^3 respirable coal dust environment. Dust reduction rates from Test-2 to Test-6 are in the range of 5.63%–27.89%, with the highest dust reduction rate (27.89%) at S2 in Test-3. Most dust samplers have lower dust concentrations downstream of the air-cleaning fan. However, the S4 sampling data in Test-1 has a higher dust level than that of the fan inlet. Similar reasons mentioned in the limestone dust results section may also cause this dust increase downstream of the fan.

Coal dust data analysis

Table 4 shows the mean, SD, and CV for coal dust concentration at the sampling locations from six independent experiments. The data were treated the same way as for the limestone dust. The SD and the CV of the coal dust are all a little higher than that of the limestone dust. The unitless CV value is between 10% and 20%, which is good according to Brown [12]. The coal dust test results have less variance, and the test design is reasonable.

Table 4. Mean, SD, and CV for coal dust concentration (mg/m^3).

Location	Mean	SD	CV (%)
S-I	129.03	22.08	17.11
S-II	124.99	24.17	19.34
S1	116.34	15.01	12.91
S2	105.15	16.65	15.83
S3	104.31	14.98	14.36
S4	115.51	11.51	9.97

Figure 4 shows the decrease of respirable coal dust concentrations at different locations. S-I was treated as a control group. Test results were expressed as mean ± SD. The statistical differences were analyzed by ANOVA, followed by the Dunnett multiple comparison test. $p < 0.05$ was considered statistically significant. The coal dust concentrations were reduced by 18.54% and 19.21% at S2 (81.46±6.78%, $p<0.05$) and at S3 (80.79±4.10%, $p<0.05$), respectively. Coal dust reductions at S1 and S4 were 9.54% and 9.83%. These differences of the respirable dust levels were not statistically significant ($p>0.05$) as compared to S-I. The dust level at the upstream S-II is 2.90% lower than that of the S-I. Coal dust particles were better mixed inside the inner chamber than the limestone dust shown previously. The dust level at S-II is also not significantly different from the control group at S-I ($p>0.05$).

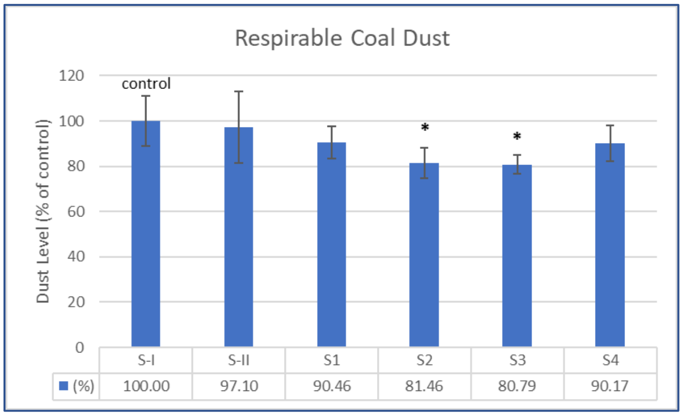

Figure 4. Respirable coal dust reduction. Coal dust concentrations were measured at six locations. Values are mean ± SD from six independent experiments. Duplicates of each location were used in each independent experiment. One-way ANOVA followed by the Dunnett posttest was used. Significance indicated by: * $p < 0.05$ vs. S-I control group.

Although the downstream coal dust levels are all lower than the upstream ones, the respirable dust concentration at the fan outlet S1 and downstream point S4 were not significantly different from that of the fan inlet point. At downstream points S2 and S3, the dust levels' difference was statistically different. However, the average total respirable dust reduction rates are both below 20%. If high respirable dust levels exist upstream of the air-cleaning fan, it may not provide a healthy environment downstream.

DISCUSSION/CONCLUSIONS

Laboratory tests of an industrial air-cleaning fan were performed in a ventilated, dual-chambered test fixture at NIOSH's Pittsburgh Mining Research Division. The dust reduction rate of the air-cleaning fan was evaluated with limestone dust and coal dust. The air-cleaning blower was installed in the vertical wall between chambers, drawing air from the inner to the outer chamber. A high respirable dust concentration was established within the inner chamber. Gravimetric dust samplers were installed in both chambers to measure the difference in respirable dust concentrations to calculate a potential reduction. Tests were repeated six times for each type of dust. When subjected to average respirable limestone dust concentrations of 98.86 mg/m^3 at the inlet of the fan, the four downstream locations measured reductions of 7.84%, 8.81%, 10.94%, and 18.02%. During coal dust tests, the air-cleaning fan reduced a background respirable dust concentration of 127.01 mg/m^3 by an average coal dust removal efficiency of 9.54%, 9.83%, 18.54%, and 19.21% at the four downstream sampling points.

As shown in this study, fan-powered inertial separation is only partially effective at removing respirable dust particles. This is likely due to their small size and the inability of the fan to sufficiently force these particles to the outside housing for separation from the main air stream. A high-efficiency respirable dust filter is recommended to be incorporated into the fan device. The addition of water spray may also help to improve the performance. These tests did not evaluate the effect of additional moisture on the device's dust-cleaning performance.

Despite these limitations, the air-cleaning fan may serve as a primary collector for other dust filtration systems in very dusty environments where air-moving capabilities are needed. Through the operation of this device, a portion of airborne particulate can be removed, extending the life of downstream filters. The ease of operation, with no regular service required, permits adoption in harsh mine environments where access may be limited. Additional modifications may be considered to improve the system's respirable-dust-removal ability and advance this technology as a low-maintenance option for dust control in mining.

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DISCLAIMER

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

CONFLICTS OF INTEREST

On behalf of all authors, the corresponding author states that there is no conflict of interest.

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APPENDIX

Table 1. Averaged respirable limestone dust concentration by filters and dust reduction rate at the downstream sampling locations.

Cases\Locations	S-I	S-II	S1	S2	S3	S4
Test 1 45-min (mg/m^3)	96.91	86.96	93.17	80.55	76.10	88.36
Dust reduction (%)			3.86 #	16.88	21.47	8.82
Test-2 (mg/m^3)	95.47	93.73	94.48	95.94	86.20	97.60
Dust reduction (%)			1.04	-0.49	9.71	-2.23
Test-3 (mg/m^3)	110.66	103.07	93.04	94.57	93.98	97.06
Dust reduction (%)			15.92	14.54	15.07	12.29
Test-4 (mg/m^3)	95.36	84.04	74.86	77.99	69.49	81.28
Dust reduction (%)			21.50	18.21	27.12	14.76
Test-5 (mg/m^3)	102.79	83.14	85.44	84.96	75.85	85.57
Dust reduction (%)			16.88	17.34	26.21	16.75
Test-6 (mg/m^3)	85.15	89.14	90.53	85.86	77.89	87.99
Dust reduction (%)			-6.32	-0.84	8.53	-3.34

Notes: #: $\text{dust reduction \%} = \frac{\text{dust concentration at S-I} - \text{dust concentration at each downstream location (S1, S2, S3, and S4)}}{\text{dust concentration at S-I}} \times 100\%$

Table 3. Averaged respirable coal dust concentration by filters and dust reduction rate at the downstream sampling locations.

Cases\Locations	S-I	S-II	S1	S2	S3	S4
Test-1 (mg/m^3)	101.63	93.26	94.50	80.56	78.27	101.88
Dust reduction (%)			7.02#	20.73	22.98	-0.25
Test-2 (mg/m^3)	112.14	124.09	105.42	89.84	94.51	102.43
Dust reduction (%)			5.99	19.88	15.72	8.66
Test-3 (mg/m^3)	145.74	126.89	121.06	105.09	115.10	116.55
Dust reduction (%)			16.93	27.89	21.02	20.03
Test-4 (mg/m^3)	134.07	117.54	119.13	118.21	107.91	125.50
Dust reduction (%)			11.15	11.83	19.51	6.39
Test-5 (mg/m^3)	140.73	127.46	125.94	111.15	110.69	118.93
Dust reduction (%)			10.51	21.02	21.35	15.49
Test-6 (mg/m^3)	139.88	160.71	132.01	126.03	119.38	127.73
Dust reduction (%)			5.63	9.90	14.66	8.68

Notes: #: $\text{dust reduction \%} = \frac{\text{dust concentration at S-I} - \text{dust concentration at each downstream location (S1, S2, S3, and S4)}}{\text{dust concentration at S-I}} \times 100\%$