Evaluation of two-phase spray system for airborne dust control in a longwall gallery

B.K. BELLE*, R.V. RAMANI† and J.F. COLINET‡
*CSIR-Miningtek, Pretoria, South Africa
†Pennsylvania State University, USA
‡Pittsburgh Research Laboratory, NIOSH, USA

The increased effectiveness of a two-phase spray system (TPSS) over a single-phase spray system (SPSS) for dust suppression is reported in several laboratory studies. The dust collection efficiencies of SPSS and TPSS were studied in a model experimental longwall gallery facility at Pittsburgh Research Laboratory at NIOSH (USA). The experimental design consisted of two factors: pressure, and airflow. Each factor had three levels. SPSS experiments were conducted at only one pressure (1035 kPa) which is nearly 1.5 times higher than the highest air and water pressure for TPSS experiments. The results of the study are presented in this paper.

While it appears that TPSS performed better than SPSS, the data is not sufficiently conclusive on this aspect. The differing spray characteristics of the chosen TPSS and SPSS nozzles did not allow a direct comparison of the two systems. In the TPSS arrangement, considerably greater turbulence in airflow is created around the shearer; it is likely that at least in the immediate vicinity of the tailgate drum, there is a roll back of the dust/mist cloud into the walkway. Therefore, positioning of the personnel upwind of the tailgate drum is necessary to avoid high dust exposures. The rate of decrease in concentration with TPSS is higher than that with SPSS. This may be due to the greater atomization of the water. The test set-up did not allow the study of conditions when coal is cut from tail to head where the potential for personal exposure is high. Changes in the experimental design are necessary to overcome some of the reasons expected for the inconclusive results.

Introduction

The most common method to control the airborne dust in longwall is through water sprays mounted on the shearer cutting drums[1]. Techniques implemented for the control of shearer-generated dust included high drum water flow rates[2], improved cutting techniques[3,4], shearer clearer-type external water spray systems[5], and radio-remote control[6]. It has been suggested that to move air and redirect the dust away from the operator in a longwall face, the external spray pressure should be at least 1035 kPa. To suppress dust before it becomes airborne, drum spray pressure should be kept below 690 kPa[7]. Several laboratory studies have shown[8–13] that the dust collection efficiency of TPSS is greater than that of SPSS. In view of these positive laboratory results, a study was planned at the model mine gallery, at the Pittsburgh Research Laboratory.

The model longwall gallery at the Pittsburgh Research Laboratory consisted of a simulated longwall face, a model double-ended ranging drum shearer, and a face ventilation system capable of generating a wide range of ventilation rates. The gallery is 37.8 m long and simulates a 2.13 m high coal face. The model longwall has 24 wooden shields along the face. The double-drum shearer is 11.9 m long and 0.96 m wide; the diameter of the drums is 1.6 m. The drums rotate to simulate the effect of rotation on air and dust behavior. The drum spray nozzles used in this study were Spraying Systems H-1/4U-0010 and H-1/4U-0015 solid stream nozzles. The headgate drum had 7 nozzles of the 0010 type and 26 of the 0015 type, while the tailgate drum had one nozzle of 0010 type and 32 of the 0015 type. Water is supplied to the shearer with a 450 L/min pump operating at pressures up to 1380 kPa. One water line supplies the drum sprays at a pressure of 552 kPa, while another supplies the sprays mounted on the shearer body and can be changed to that required for experimental conditions. Each line is fitted with a flow meter and a pressure gauge. The drum sprays are fed through a rotary union. The spray system, mounted on the shearer body (the shearer-clearer sprays) is designed for exchangeable nozzle configurations. These were the nozzles that were studied in the SPSS and TPSS experiments. The shearer body sprays are pointed toward the drums, and spray over the ranging arm to wet material within the cutting and loading zones. The gallery is ventilated by an adjustable vane-axial fan with a maximum capacity of 14.2 m^3/s. The maximum face air velocity attainable is 2.54 m/s.

Experimental design

Two sets of experiments were designed for the study. The design considered two factors that are readily changeable in a mining operation. The factors are (a) spray water and air pressure and (b) air quantity in the face. Each factor had 3 levels. In the TPSS experiments, the pressures ranged from 414 kPa to 690 kPa, and air velocity ranged from 1.52 m/s to 2.54 m/s. In the SPSS experiments, the effect of changing air velocity for a single test pressure of 1035 kPa was evaluated. In all the test conditions, the drum sprays' pressure was maintained at 552 kPa. For each test condition, two experiments were conducted. A total of 24 experiments were performed.

Coal dust and particle size distributions

Bituminous coal dust was used in the experiments as the feed dust. The size distribution of the feed dust was obtained through Microtrac Particle Size Analyzer (PSA). Samples of the feed dust were obtained directly by random collection of the coal dust from the feeder. For determining the size distribution of the airborne dust along the gallery, airborne dust samples were obtained using cascade impactors.

Dust feeder

Two mini eductors utilized compressed air at 345 kPa to transport dust through two hoses to the shearer drums. A pressure gauge and a regulator were installed in the compressed air supply line to monitor and control the air feeding the mini eductors. The compressed air entering the mini eductors passed through a venturi like section in the eductors, which induced the dust feed into the air stream. Two screw feeders discharged coal dust at rates of 0.0355 kg/min and 0.0545 kg/min through the head gate drum and tailgate drum respectively. The approximate location of these dust sources are shield 10 and shield 15, respectively.

Spray nozzles

The nozzle selected for the SPSS experiments was a 3/8 BD-3 hollow-cone hydraulic spray nozzle (Model No T47886-2). For the TPSS experiments, the air-atomizing nozzle used was of the type Model No 1/4J-SU-22.

SPSS and TPSS set-up

The number of sprays in the shearer-body (the shearer-clearer spray bar system) is 10. The spray bars had been designed to provide clean water and air for both the hydraulic and air atomizers. For the TPSS experiments, the spray manifolds are assembled on a new spray bar, so that there was the same number of nozzles with nearly the same spacing between the nozzles as in the SPSS experiments. High-pressure compressor and water pump were used to obtain the required air and water pressures for the tests. Pressure regulators and control valves were used to adjust and maintain, as far as possible, constant air and water pressures and the rate of water flow during an experiment.

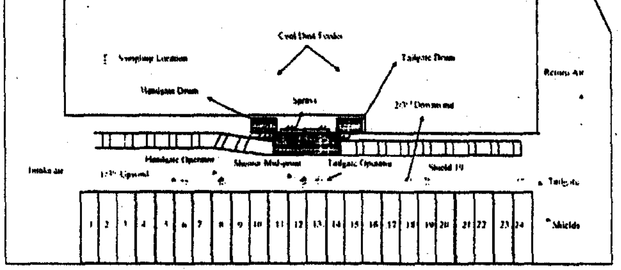

Figure 1. Schematic view of the model longwall gallery

Sampling plan

The sampling plan is shown in Figure 1. For each test, gravimetric samples were collected at the 1/3rd upwind of the shearer (shield 6), headgate operator (shield 8), shearer mid-point (shield 12), tailgate operator (shield 13), shield 19, 2/3rd downwind of the shearer (shield 18), tailgate (shield 24) and at the return. Two gravimetric respirable dust samplers, operating at 2 L/min, were used to sample respirable dust concentrations at each of the sampling locations. Excepting in the return, the units were suspended from a hanger in the approximate breathing zone of the operator. In the return, two samplers were suspended at the top, middle and bottom locations.

Real-time aerosol monitors (RAM-1), were used to supplement the gravimetric samplers at selected locations. RAMs are positioned at 1/3rd upwind of the shearer, headgate operator, tailgate operator, 2/3rd downwind of the shearer, shield 19 and at the return. In the return location, cyclones for RAM-1 were located at approximately 0.51, 1.02, and 1.52 metres from the roof. The cyclone preseparator for each RAM was suspended between the two cyclones used for gravimetric sampling and connected to the RAM with Tygon rubber tubing. Data loggers were used to record instantaneous dust concentrations. In addition, the output of the RAMs in the return station was transmitted to the multi-channel strip chart recorder in the control room for monitoring during the test.

Sampling time

From the shake-down test, it was observed that after about 10 minutes from the start of the experiment, the dust concentration in the gallery stabilized. Therefore, the sprays were turned-on after 10 minutes. Excepting for the samplers at the intake, and headgate shearer operator position, a sampling time of 75 minutes from the time the sprays were turned on, was sufficient for all other sampling locations to obtain the necessary weight gain on the gravimetric filters. During the experiment, the sampling packages at the headgate operator, tailgate operator, and shield 19 position were moved to the next downwind shield after 15 minutes of sampling at one shield. The purpose of this method of sampling was to obtain the dust profile around the shearer from the RAM charts, and assess the exposure potential of the shearer operators.

Experimental procedure for TPSS and SPSS

The following procedure was followed for each of the experiments.

- Firstly, all the gravimetric samplers, and RAMs fitted with data loggers were positioned according to the sampling plan. The water and air supply systems were checked for the highest and the lowest pressure ranges which can be attained during the experiment. Throughout the experiment, water and air pressures and the airflow were monitored and recorded automatically. The monitored data are frequently checked both on instant dials and the strip charts. The RAMs were turned on.
- Secondly, the fan, the dust injection system, and shearer drums, were switched on, and sufficient time (>10 minutes) was allowed for the experimental conditions to stabilize. The air velocity and the concentration in the return were monitored in the control room.
- When the flow conditions stabilized (>10 minutes), the

drum sprays were turned on. The spray system (SPSS or TPSS) under investigation was also turned on after a lapse of 2 to 3 minutes, and the water and air pressures, and water flow were increased to the experimental conditions. Then, the gravimetric samplers were also turned on.

- After sampling for fifteen minutes at a location, the sampling packages at locations, headgate operator, tailgate operator, and shield-19 were moved to the immediately downwind shield.
- After at least 75 minutes, the gravimetric samplers and the RAMs were switched off. The dust feeder and shearer drums, and the water and air to the nozzles were also turned off in that order.
- Finally, the dust samples were removed from the samples for gravimetric analyses. The data loggers are processed to download the data onto a personal computer and a software package was used to calculate average dust concentrations for the base and the test periods.

Data acquisition

In each experiment, the following data were collected:

- Air velocity in the gallery, water and airflow rate through the nozzle, and water and air pressures.
- The gravimetric dust samples at specified locations.
- The impactor samples at specified locations.
- Instantaneous concentrations recorded by RAMs at specified locations.

Data analysis procedure

Concentration and size analysis

Using the data collected above, the following information is generated: (a) The gravimetric dust concentrations at different locations along the longwall gallery, (b) The size distribution of the airborne dust along the longwall gallery, and (c) The total number of droplets generated in both SPSS and TPSS at different pressures.

An example of the typical output from the RAM is shown in Figure 2. This specific chart is for the RAM at shield 19 during the TPSS experiment at 690 kPa pressure and 1.524 m/s air velocity. As the RAM is moved from shield 19 to shield 23, there is a decrease in the dust concentration. This may be the result of dust knockdown as well as dust dilution. The average return concentration for each test was calculated as the arithmetic average of the individual dust concentrations for the six return samples.

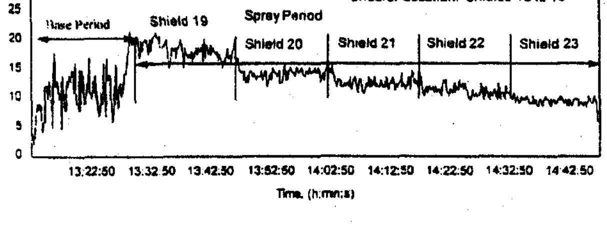

Figure 2. Typical RAM-1 output from a test along the longwall gallery

Power consumption

The power consumption calculated here is the cross product of the volume of fluid flow and the pressure drop across the nozzle[14]. This energy does not include line losses, pump and motor efficiency. For the TPSS nozzle, power input to the nozzle consists of the sum of power supplied for the water and air. In SPSS, it is only the power supplied by water. The air power required for a TPSS nozzle is given by:

$$HP_{air} = 0.221 * SCFM * \left((Pa/14.7)^{0.2888} - 1\right) \qquad [1]$$

where SCFM is the air quantity flowing through the nozzle m^3/s, and Pa is the absolute pressure in kPa.

The water power required for a TPSS nozzle is given by:

$$HP_{water} = (GPM * PSIG)/1714.3 \qquad [2]$$

where *GPM* is the water quantity flowing through the nozzle in L/min, and *PSIG* is the gauge water pressure in kPa.

Number of droplets and droplet size

For the SPSS and TPSS nozzle, the droplet size for the specified water/air pressures were obtained from the manufacturer. The number of droplets generated per minute for a particular set of operating conditions was calculated using the following equation by Alaboyun[11].

$$N_D = \frac{M_L}{M_D} = K_2 \frac{6M_L}{\pi\rho_L(R_D)^3} \qquad [3]$$

where,

K_2 is the constant (value depends on the units used)
N_D is the number of droplets generated /minute
M_L is the mass rate of water flow, g/minute
M_D is the mass of a droplet, g/droplet
R_D is the droplet diameter, µm
ρ_L is the liquid density, g/m^3.

Results

Several prior investigations have provided data to conclude that measurements of airborne dust concentrations are associated with variabilities arising from several uncontrollable factors[15]. In this experimental study, airborne dust concentration was measured in the return without turning on the sprays prior to each experiment. The plot of the average respirable dust concentration at the return *without the sprays on* is shown in Figure 3. Here, the average dust concentration at the return was calculated as

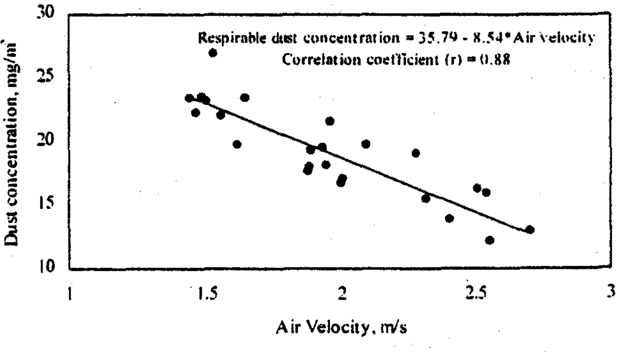

Figure 3. The plot of air velocity vs. average dust concentration in the return

arithmetic mean of the RAM dust concentrations from the top, middle and bottom levels. As expected, with increase in air velocity there is a decrease in the dust concentration and the relationship is linear. However, the coefficient of determination of 0.78 (correlation coefficient = 0.88) indicates that 22 per cent of the variance in the data is not explained by using the velocity factor alone as the independent variable. This is an indication of the several factors other than velocity, which cause variability in dust measurements during each experiment.

Size distribution of airborne dust

Two experiments were conducted at air velocities 1.68 m/s and 2.37 m/s in the longwall gallery to determine the changes in the size distribution of the airborne dust as it flowed in the gallery. For this purpose, impactors were set-up at shields 18, 21 and 24. The impactors were operated for a period of 60 minutes with a sampling rate of 2 L/min. During these experiments, dust was released but all sprays were turned off. Based on the mass of dust on each stage in the impactor, the concentrations as well as the size distributions of the airborne dust in gallery were calculated. The size distribution of the feed dust is shown in Figure 4. The total weight of the dust collected in the impactor at shield 18 is lower as compared to those at shields 21 and 24. At a velocity of 2.37 m/s, airborne dust at shields 18, and 24 have greater proportion of fines than in the feed dust. Their distributions also appear to be fairly close.

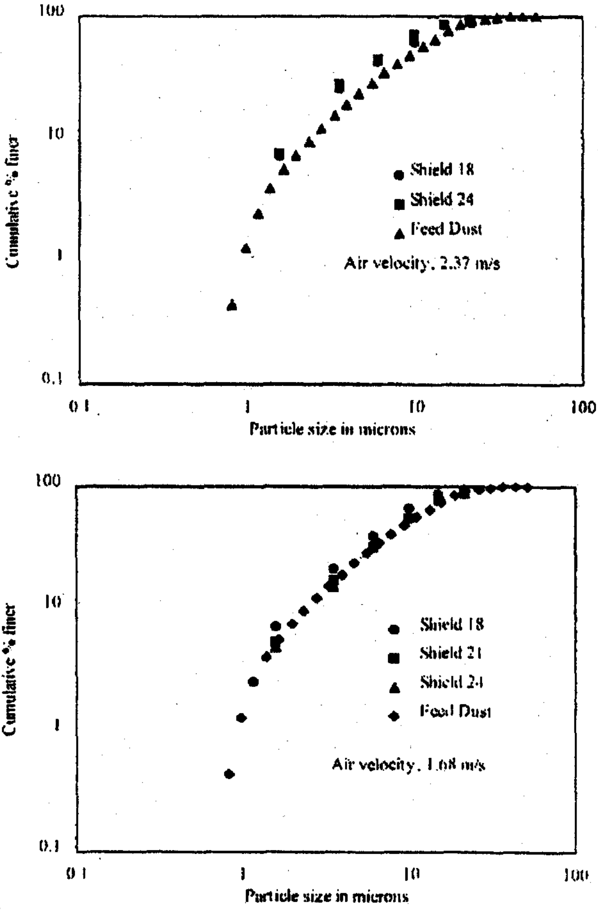

Figure 4. Size distribution of coal dust along the longwall gallery (2.37 m/s and 1.68 m/s)

Table I.
Summary of the droplet size and number of droplets

Spray Type	Pressure kPa	Volume of Water L/min	Mass of Water, g/min	Droplet Size μm	Number of Droplets/min
SPSS	690	32.17	32172.5	290	2.52E+09
	828	34.06	34065	260	3.70E+09
	1035	39.74	39742.5	250	4.86E+09
TPSS	332/311	22.71	22710	75	1.03E+11
	449/414	23.84	23845.5	85	7.41E+10
	587/538	26.49	26495	95	5.90E+10

However, the results at the lower velocity of 1.68 m/s do not follow this trend. The impactor data at shield 18 shows a greater proportion of fines than in the feed dust. The airborne dust size distributions at shields 21 and 24 appear to be identical, and have fewer fines than at shield 18. The size distributions also appear to be closer to that of feed dust. Deposition and agglomeration are two phenomena affecting changes in the size distributions of the feed dust and airborne dust. The measurement of the airborne dust size distribution by impactor may also be a contributing factor to the differences observed in these results.

Droplet size and number of droplets

The droplet sizes and the total number of droplets at different pressures in SPSS and TPSS experiments are shown in Table I. The droplet size data were provided by the manufacturer whereas the data on the number of droplets were calculated using Equation [3]. The data indicate that a SPSS droplet is comparatively larger than a TPSS droplet size in all cases, and the number of droplets in TPSS is about 20 times more than that in SPSS.

SPSS results

The SPSS experiments were performed at one water pressure (1035 kPa) and three face air velocities (1.52 m/s, 2.03 m/s and 2.54 m/s). The average of the two gravimetric dust concentration measurements at the various sampling stations are shown in Figure 5. The concentration data obtained from the tailgate station is not used in the discussion here due to the fact that due to its location, the airflow at the station is not representative of the airflow in the face. The patterns of dust concentrations at the three velocities are similar. As expected, the increased air velocity in the gallery causes, a decrease in dust concentration. The concentrations at the headgate operator (shield 6) and shearer mid-point (shield 12) are lower than

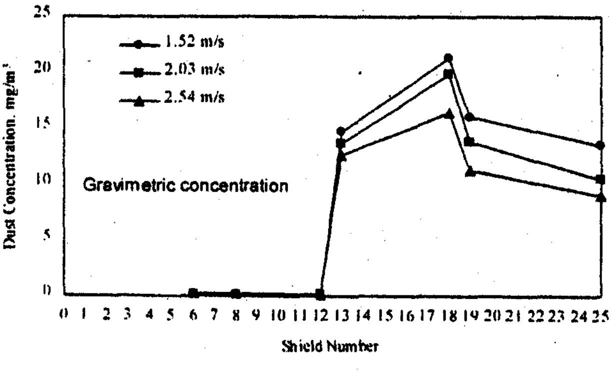

Figure 5. Average dust concentration levels along the longwall gallery in SPSS

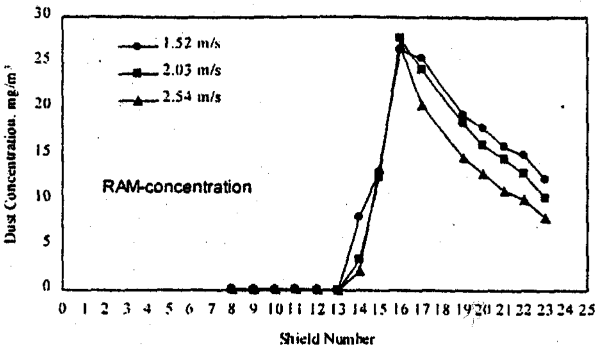

Figure 6. Average RAM-dust concentration levels along the longwall gallery in SPSS

those at the tailgate operator (shield 13). Immediately downwind of the head gate drum (shields 11 and 12), the concentration does not increase. However, it rises steeply downwind of shield 12, exposing the tailgate operator to the headgate drum dust. Immediately downwind of the tailgate operator (shield 13), the concentration increases from the tailgate drum dust source. However, after shield 16, it decreases towards the tailgate. Overall, the concentration at the return station is lowest when compared to that of tailgate operator (shield 13), 2/3rd downwind of the shearer (shield 18) and shield 19.

In Figure 6, the average dust concentrations measured by the RAMs at each shield from shield number 8 to shield number 23 are shown for the three velocities. These concentrations are calculated from the RAM plots for each experiment. The dust profile for the locations, 1/3rd upwind of the shearer, headgate operator and return location for different test conditions, were of similar pattern. As the shearer is between shield 10 and shield 16, it is evident that the shearer dust contamination of the walkway air starts between shield 13 and 14 and increases to a maximum between shields 16 and 17. The effect of increased air quantity on concentrations is more pronounced downwind of shield 16. These data indicate that the location of miners downwind of shield 14 is not advisable.

TPSS results

The TPSS experiments were performed at three air/water pressures (414 kPa, 552 kPa and 690 kPa) and three face air velocities (1.52 m/s, 2.03 m/s and 2.54 m/s). The average of the two gravimetric dust concentration measurements at the various sampling stations is shown in Figure 7 (left plot). The pattern shown is similar to that of SPSS results. As in the case of SPSS, the concentrations at the headgate operator and shearer mid-point are quite low whereas those at the tailgate operator are comparatively very high. As shown in Figure 8, for a constant pressure, increase in airflow decreases the dust concentration at the stations. On the other hand, though pressures higher than 414 kPa lead to lower concentrations at all stations except at shield 18, the effect of increasing pressure at a constant airflow on concentration is not as distinct.

In Figure 7 (right plot), the average dust concentrations

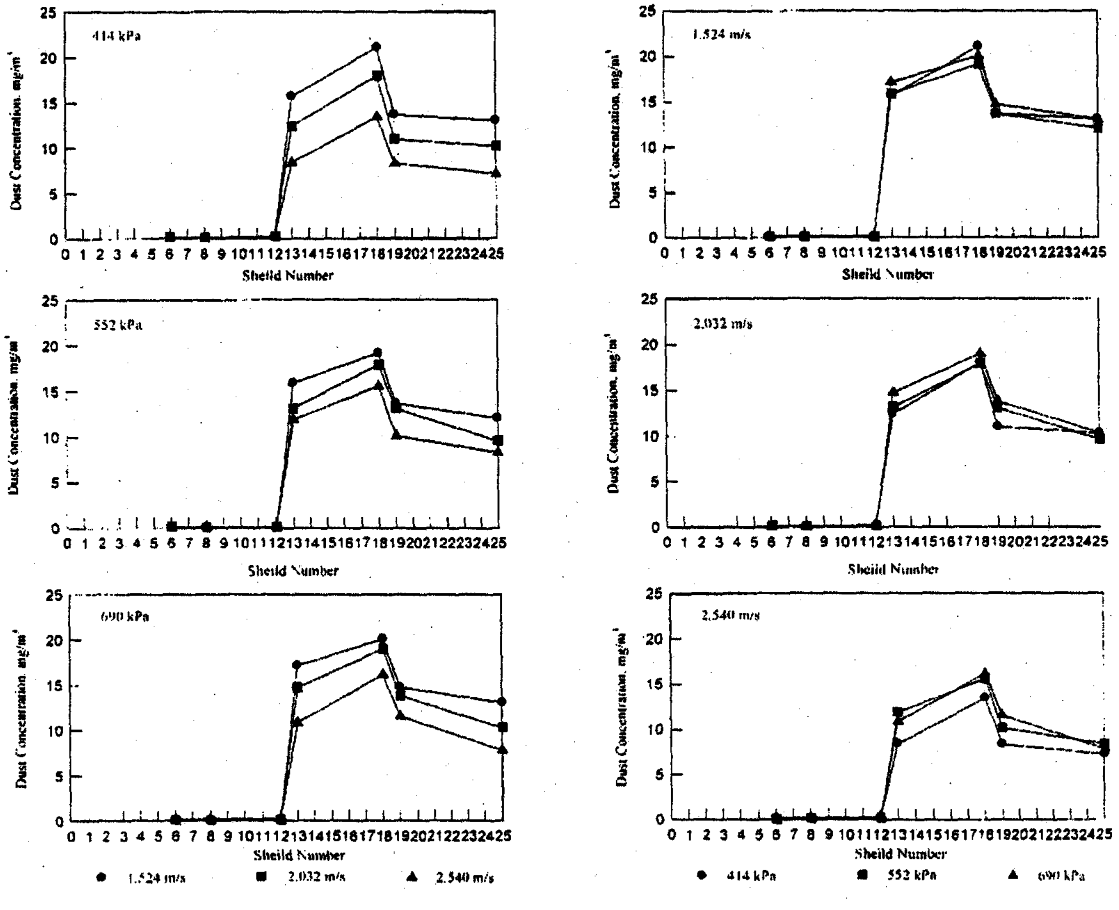

Figure 7. Average dust concentration levels (left plot) and average RAM-dust concentration levels (right plot) along the longwall gallery in TPSS

measured by the RAMs at each shield from shield number 8 to shield number 23 are shown for the three air velocities. The pattern of dust concentration increase around the shearer is similar to that noted in SPSS. Higher RAM concentrations in all the eighteen experiments (3 pressures × 3 air velocities × 2 replicates) was reached at shield 16. In all cases, these concentrations are higher than the highest SPSS concentrations (3 pressures × 2 replicates = 6 experiments). The increase in dust concentration levels between shield numbers 13 and 18, probably resulted due to the rollback of dust onto the walkway. As opposed to the experiments reported in a continuous miner gallery or a laboratory set-up[10,12], the walkway location in the longwall gallery is relatively close to the sprays for the dust rollback to influence the ambient concentration in the walkway. The decrease in the dust concentration from shield 19 towards shield 24 is due to knockdown, deposition and diffusion of the dust.

In the RAM data, the highest concentration for both TPSS and SPSS was noted at shield 16. In SPSS, this concentration was 27.74 mg/m³ at 2.03 m/s velocity. In TPSS, the experimental condition at which the highest concentration observed was 690 kPa pressure and 1.52 m/s velocity. The highest concentration was 38.61 mg/m³. RAM samplers have shown to be affected by water sprays and the smaller droplet size and greater number of droplets with TPSS may have more impact on the RAMs. Gravimetric results suggest that, in general, dust levels with TPSS were equal to or less than dust levels with SPSS (Figures 5 and 7 [left plot]).

Using the RAM data, the rates of change of concentrations in SPSS and TPSS were calculated for the following locations and are shown in Table II: (a) the rate of increase in concentration from shield 14 to shield 16, (b) the rate of decrease in concentration from shields 16 to 19, and (c) the rate of decrease in concentration from shields 19 to 23. In TPSS, the average rate of increase of concentration from shields 14 to 16 is lower with higher pressures. The average rates of decrease in concentration between shields 16 and 19, and shields 19 to 23 in TPSS are also lower at higher pressures. When SPSS results are compared with TPSS results, it is noted that there is no consistent pattern. However, the higher rates of decrease in concentration in TPSS may be the result of greater atomization of spray. These results suggest that the performance of TPSS is better than SPSS downwind of the shearer.

Water and energy consumption in SPSS and TPSS

The water consumptions at different pressures in both SPSS and TPSS are shown in Figure 8 (top plot). At all pressures, the water consumption in SPSS is higher than those in TPSS. In TPSS, at 690 kPa water and air pressure, the water consumption is 26.45 L/min. In the case of SPSS, at 1035 kPa, the water consumption is 39.74 L/min. The power consumptions in SPSS and TPSS are shown in Figure 8 (bottom plot). TPSS consumes approximately six times more power than SPSS at high pressure.

Table II
Rates of change of concentration in SPSS and TPSS

	SPSS			TPSS								
	1035 kPa			414 kPa			552 kPa			690 kPa		
	Face Air Velocity, m/s			Face Air Velocity, m/s			Face Air Velocity, m/s			Face Air Velocity, m/s		
	1.52	2.03	2.54	1.52	2.03	2.54	1.52	2.03	2.54	1.52	2.03	2.54
Rate of increase, Shield 14 to 16, mg/m³/shield.	9.18	12.15	12.35	11.73	13.41	15.84	10.46	10.94	13.26	13.04	9.96	8.21
Average	11.23			13.66			11.55			10.40		
Rate of decrease, Shield 16 to 19, mg/m³/shield	2.35	3.13	4.10	2.89	3.79	7.69	4.13	3.09	4.29	5.96	3.67	1.65
Average	3.19			4.79			3.84			3.76		
Rate of decrease, Shield 19 to 23, mg/m³/shield	1.77	2.04	1.64	2.41	2.75	1.46	2.07	1.58	1.99	0.81	1.84	1.86
Average	1.82			2.21			1.88			1.50		

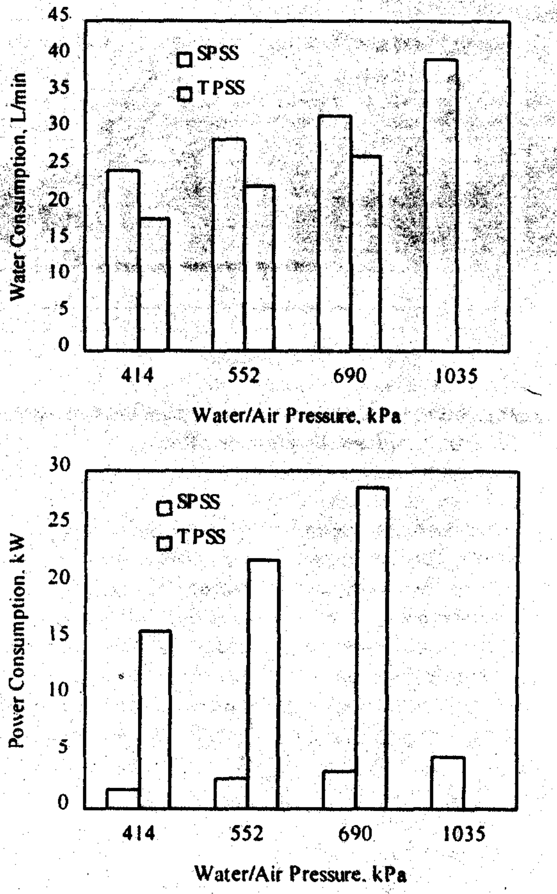

Figure 8: Water consumption (top plot) and power consumption (bottom plot) in TPSS and SPSS

Comparison of SPSS and TPSS results

The highest gravimetric concentration in SPSS and TPSS experiments was at the 2/3rd downwind station (shield 18). In SPSS, this concentration was 21.34 mg/m³ at 1.52 m/s velocity. In TPSS, the experimental conditions at which the highest concentration observed were 414 kPa pressure and 1.524 m/s velocity. The highest concentration was 21.08 mg/m³.

Conclusions

The dust collection efficiencies of SPSS and TPSS were studied through experiments in a model longwall gallery. The experimental design consisted of 2 factors: spray water and air pressure, and ventilating airflow. Each factor had three levels. The differing spray characteristics of the chosen TPSS and SPSS nozzles did not allow a direct comparison of the two systems.

In the present experimental set-up, the dust rollback into the walkway may be a factor in the case of TPSS. Other important observations from this study are noted. The rate of decrease in concentration with TPSS is higher than that with SPSS. This may be due to the greater atomization of the water. Positioning of the personnel upwind of the tailgate drum is necessary to avoid high dust exposures.

The present set-up did not allow the study of conditions when coal is cut from tail to head where the potential for personal exposure is high. Changes in the experimental design are necessary to overcome some of the reasons expected for the inconclusive results. Some suggested areas are experiments with same nozzle types, same pressure conditions and higher TPSS pressures. This might have created a different air flow pattern around the shearer. While it appears that TPSS performed better than SPSS, the data is not sufficiently conclusive on this aspect.

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