FINAL PROGRESS REPORT

TITLE PAGE

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LIST OF TERMS AND ABBREVIATIONS

CDC	Centers for Disease Control
CWP	Coal workers' pneumoconiosis
DSD	Drops size distribution
EPA	Environmental Protection Agency
NIOSH	National Institute of Occupational Safety and Health
PMF	Progressive massive fibrosis
PSD	Particle size distribution

ABSTRACT

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In spite of significant efforts that have been made to protect the respiratory health of mine workers, exposure to coal dust, silica dust, diesel particulate matter and other suspended particles continues to threaten the pulmonary health of the mining work force. This is true in both surface mining and underground mines. Within the mining work force illnesses that continue to be common are silicosis and coal workers' pneumoconiosis (CWP or black lung disease). Of greatest threat to respiratory health are particles that are approximately one micron in diameter. Particles which are much larger than this size range tend to be captured in the oropharyngeal area of the human respiratory system. However, significant alveolar deposition occurs for particles ranging in diameter from 0.01um to 10um (EPA, 1999).

Water sprays are used in many aspects of mining in an attempt to reduce the level of particulate matter in the air that is breathed by the mining work force. Sprays are used to wet the gallery walls where cutting occurs, as well as to wet recently cut rock and coal. Additionally, sprays are employed in wet scrubbers that are used in the cabs of mining vehicles. Wet scrubbers are also used on the sides of continuous mining machines where air is pulled from the cutting region, directed through the scrubbers and then returned at the rear of the continuous mining machine in the vicinity of the operator. Unfortunately, while water sprays can be very effective at removing relatively large and very small particles from air, for particles precisely in the 0.01 to 10 um range that are most dangerous to respiratory health, water sprays are relatively ineffective.

Because a large installed base of water spraying nozzles and affiliated equipment already exists, the focus of the proposed work was to improve the efficacy of such sprays, rather than to develop a completely different method for lowering dust levels in mines. Specifically, the use of ultrasonic excitation of the spray was proposed as a means for improving the ability of sprays to scavenge particulate matter from the air. In this work, an ultrasonic standing wave was generated between an ultrasonic transducer and a reflector. This standing wave field forms 'accretion disks' in the air. These are regions where the air flow collects and anything that is suspended in the air is concentrated. A spray was directed through this standing wave field, along one axis, and a particle-laden air stream was directed through the standing wave field along a perpendicular axis. In the accretion disks, the particles and the spray drops were concentrated and brought into close proximity with each other. The spray drops grew and fell to the floor, removing particles with them. In short, a small scrubber was developed, where ultrasonics were used to increase the ability of the spray to remove particles. Improvements of nearly 150% were attained.

SECTION 1

Significant (Key) Findings:

The most important result of this research was the discovery of "accretion disks" which form when an ultrasonic standing wave field is created. These accretion disks are regions of low pressure at the nodes of the standing wave field where droplets and particles collect. The importance of this result is that these accretion disks bring drops and particles into a confined region, forcing them to come into contact with each other. This increases the probability that particles will be scavenged by drops. In a typical wet scrubber, sprays are directed in one direction, and a flow of particle laden air is flowed in the opposite direction. The chance of a particle and drop coming into close proximity is dictated by the concentrations of both since, in the absence of charging, there is no force that attracts or repels the drops and particles. However, by incorporating an ultrasonic standing wave field, there is a force imposed that concentrates both particles and drops into one region, increasing the chance that spray drops will remove particles.

The second important result of this research was the development of a small scale wet scrubber that incorporated an ultrasonic standing wave field. The scrubber employed low air flow rates and low water flow rates for the sprays. An ultrasonic standing wave field was established inside of the scrubber, and it was demonstrated that the scavenging coefficient increased significantly when the ultrasonic standing wave field was in place, compared to the case without that standing wave field. The degree of improvement was itself a function of the spray flow rate, the particle size and the type of particle used (see Section 2 for details). However, improvements in the scavenging coefficient as large as 150% were observed. Especially noteworthy is that the region where improvements were especially large was for particle diameters less than 3 um. Hence the improvement in scavenging attained from using ultrasonics occurs precisely for the particle diameters of greatest concern to pulmonary health.

Translation of Findings:

The current finding cannot be translated directly to the mining workplace presently because the parameter range of air flow rate and water flow rate used in these experiments is much smaller than that used in existing scrubbers. Future investigators who might wish to implement these findings in a mining environment should conduct experiments at higher air flow rates and higher water flow rates. This would most certainly also require higher ultrasonic energies. However, it is possible that this could be avoided by instead using many ultrasonic transducers, each of which handles a subset of the total airstream. What is needed is a larger scale study where more realistic air and water flow rates are used. Also, in this research, polystyrene latex (PSL) spheres were used as a proxy for coal dust particles, since these PSL spheres could be procured at predetermined diameters with a monodisperse distribution, something which could not be done for coal. Hence, future work should focus on using actual coal dust as the particle source. Finally, the ultrasonic transducers require and electrical power source. Since the use of electrical power represents a safety issue in mines where a spark could result in an explosion, this issue also needs to be addressed in future research.

Outcomes/Impact:

The findings of this research have the potential to significantly reduce the concentration of micron scale particles in the mining environment. In this research, a small scale wet scrubber was constructed and was used to show how an ultrasonic standing wave field could be employed to increase the ability of this scrubber to remove particles from a particle laden air stream. In coal mines, continuous mining machines have wet scrubbers mounted along the lateral edges of the vehicle. These scrubbers entrain air from the gallery wall where cutting is occurring and therefore where dust levels are very high. By spraying water on this high dust level air, the scrubbers reduce the amount of particles in the air which is subsequently flowed to the rear of the continuous mining machine where the operator is typically located. This reduces the threat to the pulmonary health of the operator. However, these devices rely on sprays to remove particles from the air, and it has been shown that water sprays work well at removing large particles, but rather poorly at removing micron scale particles. The research conducted under this grant demonstrated that an ultrasonic standing wave field in a wet scrubber can dramatically improve the removal of micron scale particles. Hence, if this research can be successfully scaled up to the air flow rates and water flow rates used in these scrubbers, the threat to operators of these machines can be dramatically reduced. The same can be said of surface mines, where small scrubbers are used in the cabs of various vehicles. Utilizing the results presented herein can increase the ability of those scrubbers to remove particles, improving the quality of the air in the cabs of these vehicles, and improving the health of operators and reducing the chance that they will suffer from pulmonary illness due to exposure to silica particles.

SECTION 2 – Scientific Report

Background

This work focuses on the use of water sprays to remove particles from a particle laden stream of air. The use of sprays in this way is common in the mining industry where such sprays are used to reduce respirable dust levels by wetting broken material and cutting surfaces. Sprays are also used in scrubbers where air is entrained through a sprayed region within and passed through filters. Scrubbers are used in continuous mining machines and also in the cabs of mining vehicles (NIOSH, 1987). Although the use of sprays (as well as other dust control strategies) does reduce the level of dust in mining environments, dust levels are still problematic, and the mining industry is susceptible to higher than average rates of mortality and work related illness. Several respiratory illnesses are common to mine workers, such as silicosis from exposure to crystalline silica dust and coal workers' pneumoconiosis (CWP or black lung disease) from exposure to coal mine dust (Colinet & Flesch, 1997). Miners suffering from CWP have an increased risk of developing progressive massive fibrosis (PMF) (Page & Organiscak, 2000). While significant effort has been made to reduce the level of respirable dust in mines, deaths from pulmonary disease among mine workers remains high. Indeed, CWP was directly responsible for the deaths of 1003 US miners in 1999, (NIOSH, 2004) and an indirect cause in 20,000 more miner deaths since the mid-1980s. Furthermore, from 1995-1999, 26.2% of recorded coal mine dust exposure levels exceeded recommended exposure levels (REL), (NIOSH, 2002), and the increased use of diesel engines in underground mines has raised concerns over the threat of diesel particulate matter (DPM) to which miners are subjected. Approximately 30,000 U.S. miners are exposed to DPM levels in excess of the recommended concentration limit of 50 ug/m^3(NIOSH, 2002). The motivation of this grant was to see if there can be greater reductions in the respirable particles that exist in mines.

The ability of a spray to remove particles from an air stream is a function of the particle-drop interaction. Numerous factors affect airborne particle capture by a drop. These include the drop and particle densities, the diameters of the drop and particle, the charge on the drop and particle, the physical properties of the liquid such as surface tension and viscosity, and airflow characteristics around the drop. The ability of a drop or group of drops such as a spray, to capture a particle is quantified by the scavenging coefficient, *E*:

$$\mathrm{E} = \frac{n_s}{n_T} \tag{1}$$

where n_s is the number of particles scavenged by the drop (or collection of drops), and n_T is the total number of particles within the cylindrical volume swept out by the drop(s) as it travels through the particle laden air stream. For a given drop diameter *D*, *E* is sensitively dependent on the particle diameter *d*. Specifically, plots of *E* versus *d* reveal a minimum, in *E*; *E* can be quite low at this minimum. This minimum is the result of two competing trends. At large diameters, inertia plays a large role in particle scavenging since the particle, unable to follow the streamlines around the drop, impacts the drop. At very small diameters, these inertial effects do not play a role, but Brownian motion, modeled as diffusion, serves to enable a relatively large fraction of particles in the boundary layer near the drop to diffuse toward the drop and thereby impact the drop in that fashion.

These diffusive effects increase as *d* decreases, while inertial effects increase as *d* increases. Accordingly, there is a range of particle diameters that falls between the inertially-dominant and diffusive-dominant regimes, where neither inertial nor diffusive effects are effective, and where values of *E* are relatively low. This region where a minimum in *E* is observed is often referred to as the "Greenfield gap", after Greenfield who analytically investigated the scavenging coefficients of particles in rainfall and was first to show the existence of this minimum (Greenfield, 1957).

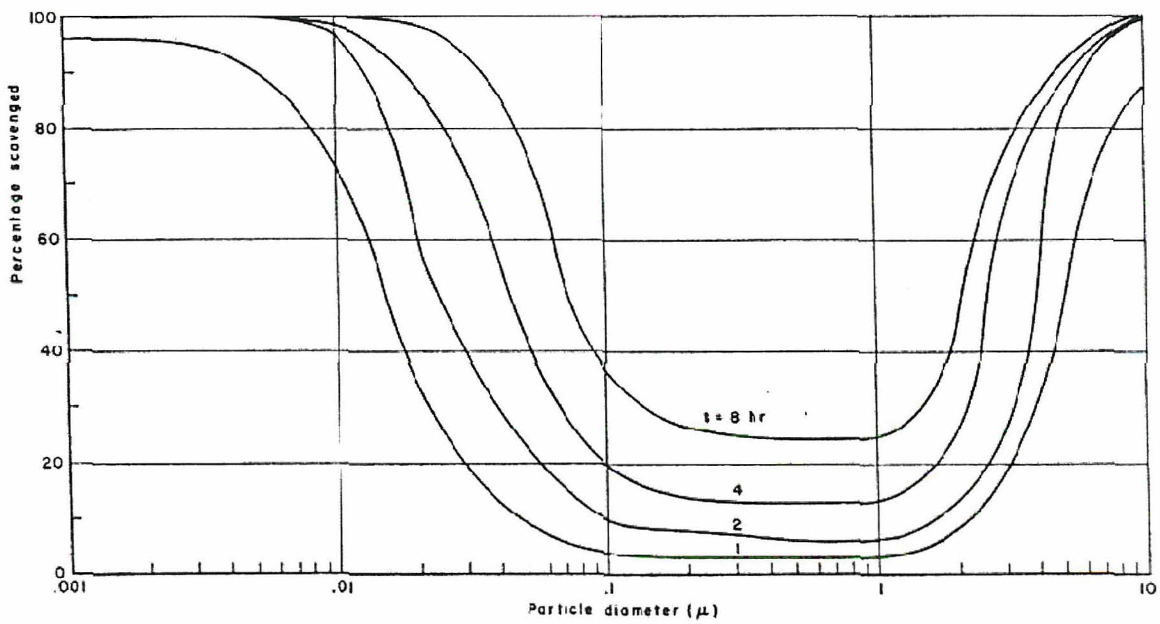


Figure 1- Plot of scavenging coefficient versus particle diameter, due to Greenfield (1957).

A plot taken from Greenfield's paper is presented in Figure 1 which shows reduced *E* for particle diameters ranging from ~0.1 um to ~1.0 um. This range will differ depending on the characteristics of the drop, the particle and the airflow, among other things. However, for applications relevant to this work where water drops have diameters ranging from several tens of microns to a millimeter, the gap in scavenging coefficient corresponds roughly to that shown in Figure 1. This was shown, for example, by Pranesha & Kamra (1996) who compiled the work of several authors, incorporating water drops where *D* ranged from 87 um to 4.8 mm and particle densities ranging from 1000 kg/m^3 to 2500 kg/m^3. Although the location of the scavenging gap varied with experimental conditions, the minimum in *E* resided between 0.1 um to 1.0 um, with few exceptions.

The existence of a minimum in *E* for particle diameters, *d* = 0.1 um - 1.0 um is of particular concern for pulmonary illness. Alveolar deposition of particles peaks for *d* slightly larger than 1 um; significant alveolar deposition occurs for particles ranging in diameter from 0.01 um to 10 um (EPA, 1999). Particles with *d* < 2.5 um (often referred to as PM2.5) are believed to pose the greatest health risk

(Schwartz, 2002). This means that the range in *d* that presents the greatest threat to pulmonary health overlaps the range in *d* where sprays are least effective in removing particles from air.

Because of the ubiquity of sprays in mining environments, a method for increasing the scavenging coefficient of spray drops for particle diameters in the 0.1 to 1.0 um range could lead to technologies that would significantly improve pulmonary health. In this work a method was explored for impvorving the spray scavenging of micron-scale particles using ultrasonics. Ultrasonics has often been used in the study of drops wherein a standing wave field in established between a transducer and a reflector (Trinh, 1985). When this is done, drops can be levitated in the nodes the standing wave field, facilitating the study of these drops. At these nodes there is a low pressure zone (pressure node) due to nonlinear effects (Marston, 2004). There are several theoretical (Lighthill, 1978) and experimental (Trinh, 1994; Hasegawa, 2009) studies of the air flow resulting from high intensity acoustic standing waves. This kind of flow is called acoustic streaming which can be complex and can also be affected by objects in the field; this type of flow is incompletely understood. However, there is evidence to suggest that a stagnation point flow is often formed near pressure nodes and is maintained when drops are present in those nodes (Trinh, 1994). In the present study we took advantage of the flow focusing effect that occurs in this stagnation point flow to force particles and drops to accrue there. Specifically, we used this flow to force particles and drops to come into close proximity with each other, increasing the chance for a drop to scavenge a particle. Moreover, in these zones drops are also likely to collide with each other, resulting in larger drops. Therefore, drops that have scavenged a particle are likely to get larger. This is important, since if small diameter drops are used, they may not fall down, instead remaining in the air stream where they may subsequently evaporate, releasing any particles that have been scavenged.

There were two main aims or thrusts to this project. The first was to determine if ultrasonics could be used to improve the scavenging of a spray. The second was to determine if/how ultrasonics could be used to excite spray drops to oscillate and thereby increase particle scavenging. To achieve the first aim, a fine mist was generated in the vicinity of the ultrasonic standing wave field. The spray could be visually observed to migrate toward the nodes, where drops combined and larger drops were observed to grow. These drops became large and eventually fell downward where they were drained away. We called these zones "accretion disks," since both the drops and, presumably, the particles, accrue in these regions. The goal of this work was to determine if, and to what degree, this process could be used to enhance particle scavenging. An experimental device was built to accurately measure the improvement of particle scavenging by a spray due to an ultrasonic standing wave field. The device was essentially a small-scale scrubber, where a stream or air laden with particles entered the scrubber. A spray was directed into the box, and an ultrasonic standing wave field was introduced, whose axis was perpendicular to the spray direction. Experiments were conducted with and without ultrasonics to show the effect of the standing wave on *E*. Experiments were conducted using monodisperse polystyrene latex (PSL) spheres, as well as with ambient particles. To achieve the second goal, an ultrasonic transducer/reflector combination was used to levitate a drop which had a flow of disodium fluorescein particles directed over it. The scavenging coefficient was measured for this drop with and without drop oscillations (achieved via frequency modulation of the ultrasonic excitation) to see the effect of these oscillations on the particle scavenging process.

Methodology

One of the thrusts of this work was to ascertain how sprays could be improved in their ability to scavenge particles. The overall approach used to achieve this was to build a small scale scrubber and determine *E* for this scrubber with and without the imposition of an ultrasonic standing wave in the region where spray and particles interacted. A fine water spray was directed downward inside the scrubber, and a flow of particle laden air entered from the upper left side and exited from the upper right side. A horizontally oriented ultrasonic standing wave field was established inside the scrubber, and experiments were conducted with and without the field. The concentration of particles was measured at the entrance and exit to the scrubber, and this was then used to compute a scavenging coefficient, *E* according to Eq. (1), as will be described in greater detail, below.

Experimental setup

The entire test facility is shown in Figure 2. The heart of this facility is the scavenging chamber which is illustrated by itself in Figure 3, and is the location where scavenging actually occurs. The scavenging chamber is rectangular with a volume of 370 cm^3. An ultrasonic nebulizer was mounted on the top of the chamber, and directed downward to create a fine water spray. The mean droplet diameter for this spray was around 90 um. Preliminary experiments were conducted to show that the ultrasonic transducer used in this nebulizer did not affect the ultrasonic standing wave field in the scavenging chamber. Specifically, a vibration sensor was inserted into the region of the standing wave field which showed that the sound pressure generated by the nebulizer was negligible compared to that of the standing waves in the scavenging chamber. Apparently, most of the nebulizer ultrasonic energy is consumed by the process of atomizing water, for which it is designed. The water flow rate for the spray ranged from 10 to 90 ml/min in these experiments, and was precisely controlled using a peristaltic pump. A water drain was located at the bottom of the chamber to drain accumulated water; this water contained the scavenged particles.

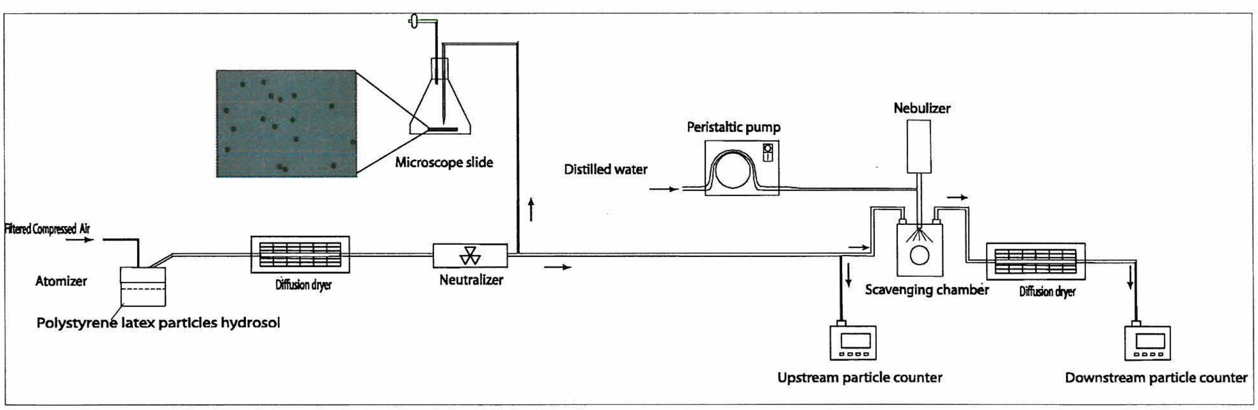


Figure 2 - Experimental apparatus.

As indicated in Figure 3, the standing wave field was established in the scavenging chamber using an ultrasonic transducer and brass reflector plate combination separated by 28 cm. The acoustic wave emanating from the transducer passed through a plexiglass tube having a diameter of 5 cm, which entered the main portion of the scavenging chamber via an air tight hole. This approach provided a clear path from the transducer to the reflector. Recessing the transducer away from the path of the spray also insured that the transducer did not get wet, which was an important factor. Preliminary experiments used a different setup where the transducer was not recessed from the main portion of the chamber. During these experiments the transducer became wet and would re-atomize the drops that landed on the transducer surface. Relatively large drops which had already scavenged a particle would subsequently be re-atomized by the transducer, potentially reintroducing the scavenged particle back into the flow. The recessed transducer approach illustrated in Figure 3 avoided this problem. The scavenging chamber was airtight except for the air flow inlets and outlets. A water drain (not illustrated) was also open to atmospheric pressure; however a layer of water was always present at the bottom of the chamber, so air did not leak out from the drain.

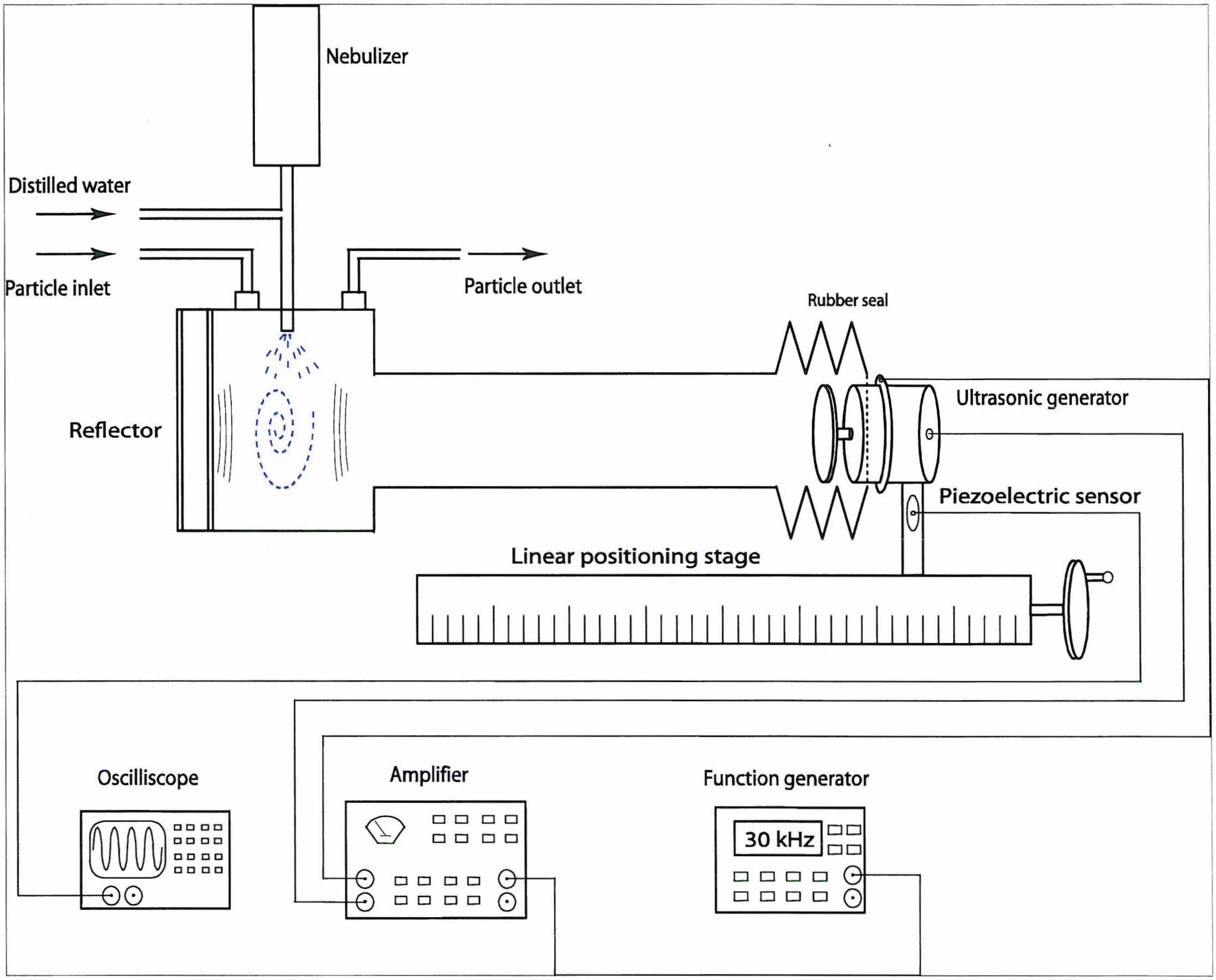


Figure 3 - Scavenging chamber.

The primary particles investigated here were polystyrene latex (PSL) microspheres having diameters of 0.7, 0.9, 2.3, 3.1, and 4.2 microns; ambient particles contained in the laboratory environment were also studied as described later. PSL was selected for several reasons. First, these particles are easily procured in highly monodisperse distributions. Hence, by atomizing solutions of these spheres, a monodisperse distribution can be formed as long as the water is completely evaporated and as long as the atomized drops had only one PSL sphere per drop. Secondly, the alternative approach of atomizing solutions of soluble salts such as sodium chloride or disodium fluorescein created potential problems in high humidity environments where phase transformation and growth could occur (Tang, 1976).

To create a monodisperse distribution of PSL in air, a PSL hydrosol supplied by Spherotech Inc. was first diluted using distilled water. After dilution the particles were washed several times using a centrifuge. During this process, the water/particle solution was spun, forcing the PSL particles to the bottom of the container after which the water residing above the particle layer was easily decanted. This process was repeated several times, thereby removing any soluble impurities. Finally, the resulting hydrosol was sonicated to disperse agglomeration of the PSL particles, and the solution was ready for use in the setup of Figure 2. A TSI model 9302 atomizer was used to atomize the diluted hydrosol into a mist which was convected through the experimental apparatus via a flow of clean dry air at a flow rate of 12 liters/min; this is labeled as "Filtered Compressed Air" in Figure 2. The dry air partially evaporated the water drops containing PSL spheres; to ensure that all water was removed, the flow was passed through a diffusion dryer (also illustrated in Figure 2) to remove any remaining moisture. PSL aerosols formed using this method have been shown to contain significant static charge (Whitby, 1967). To eliminate any potential charging problems, a NRD model P-2031 neutralizer was used, which consisted of a 20mCi polonium-210 radioactive source. This source was placed in line with the flow, downstream of the diffusion dryer.

To measure the particle size distribution (PSD), particle samples were collected by directing a portion of the airflow just downstream of the neutralizer onto a glass microscope slide. This was done via a tee fitting which directed part of the airflow away from the remainder of the experimental facility and into an Erlenmeyer flask which had a clean microscope slide located at its bottom. The microscope slide was exposed to the flow of particles during the entire course of an experimental run (~5 hours). Images of particles were then obtained using a Leica (DM750) microscope having a digital camera mount. Depending on the particle size used in a given run, the microscope was used at a magnification of either 400 or 1000. A digital camera was mounted to the microscope, and was used to acquire 100 images of each microscope slide. A separate image of a ruler was obtained and used to generate a micron/pixel conversion, which was used to obtain particle diameters from the digital images. This conversion factor varied from 0.02 to 0.05. The number of particles imaged for each experimental run ranged from 2000 to 4000, depending on the magnification and the areal deposition density on the slide which varied from experiment to experiment. An image processing algorithm was developed to convert each of the acquired grayscale images to a binary image and to then obtain the diameter of each of the particles in that binary image. This image processing algorithm began by using Otsu's algorithm to convert the grayscale image to a binary image. The image was then segmented into separate particles using a pixel connectivity criterion. The area of each particle was then obtained by summing all of the connected pixels in each particle. This area was converted to a diameter, based on the assumption that each particle was spherical. A method to detect the roundness of the object was also used to ensure that only spherical objects were counted so that the rare dust particle was not included in the measurements. A sample grayscale image of deposited particles is presented in Figure 4, and the binary version of this image obtained using the aforementioned image processing steps is presented in Figure 5.

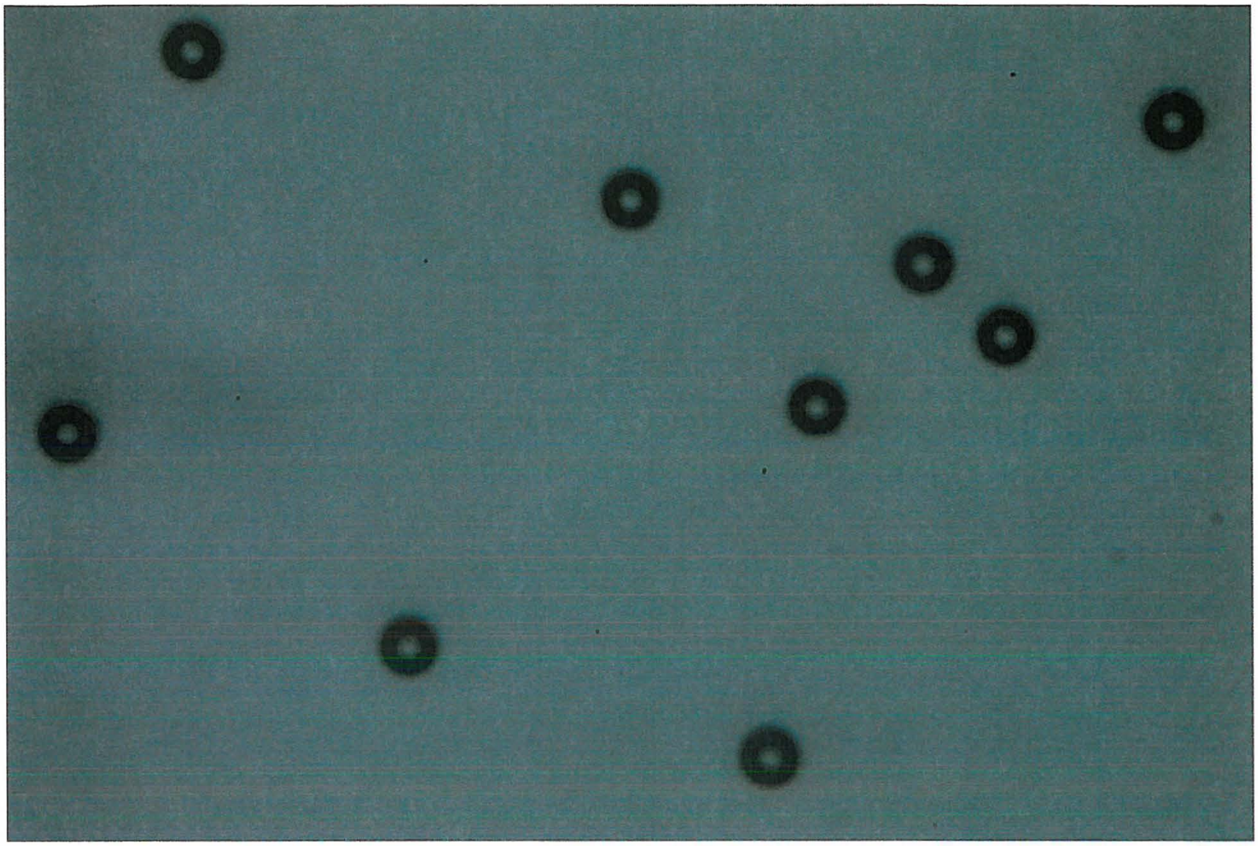


Figure 4 - Sample image obtained of PSL particles deposited on a microscope slide. This image is not processed.

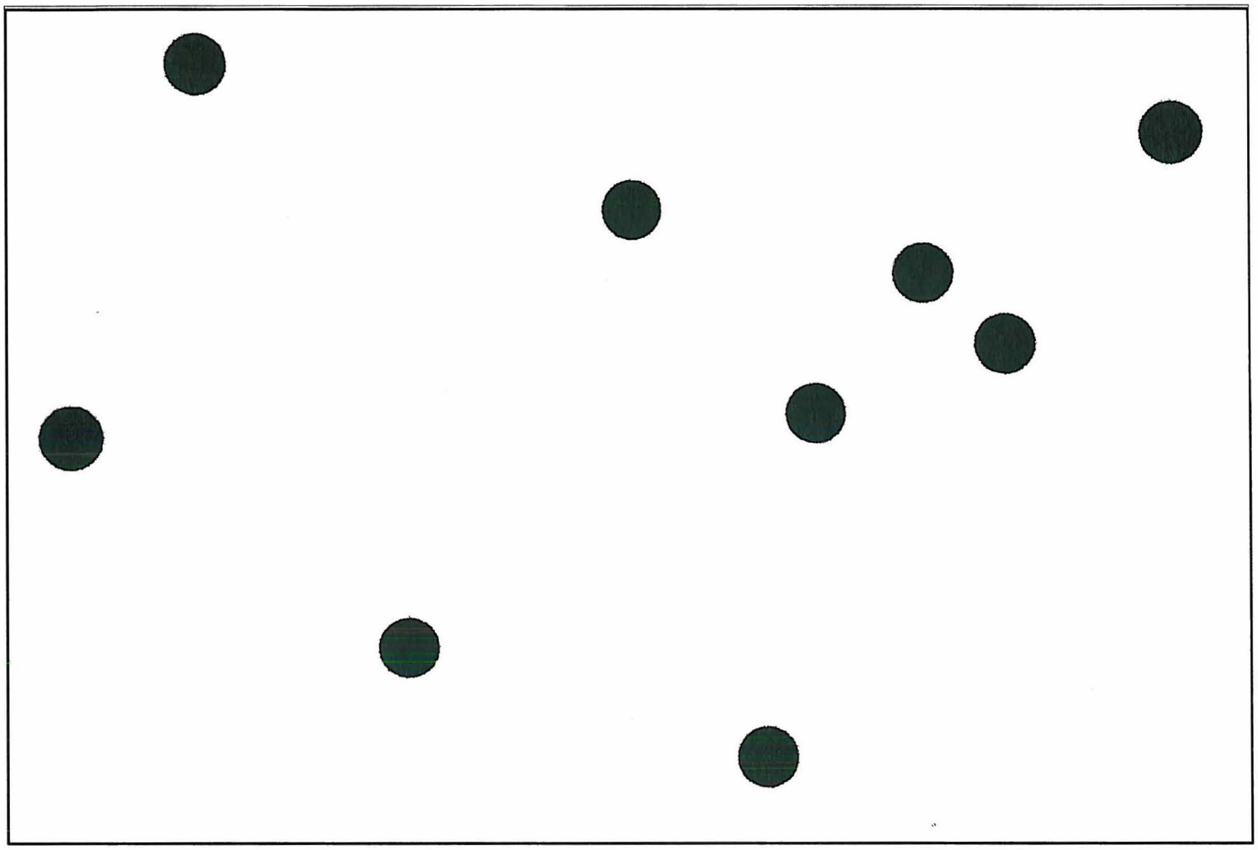


Figure 5 - Binary version of the image presented in Figure 4. This image was obtained by applying the image processing algorithm described in the text.

As noted above, PSL particles having five different diameters were employed. According to the manufacturer, the average diameters for these were 0.7, 0.92, 1.7, 2.78, and 3.8 microns. The PSDs obtained using the method described above is presented in Figure 6 for each of the five particle solutions used. The measured value of average diameters and standard deviations for each of these solutions are: 0.7 ± 0.1; 0.9 ± 0.2; 2.3 ± 0.4; 3.1 ± 0.4; and 4.2 ± 1.5 microns. While these distributions are not perfectly peaked, there is no evidence of doublets or triplets in these distributions, suggesting that the variation is due to variability in the actual particles, and not agglomeration in the atomization process. The difference between the average diameter value provided by the manufacturer and the measured value is most likely caused by inhomogeneities in the particle solutions. In solution, bigger particles tend to settle at the bottom layer due to gravity. The liquid inlet of the atomizer is located at the bottom of particle solution reservoir; this could result in a value for an average diameter different from (and slightly larger than) that quoted by the manufacturer.

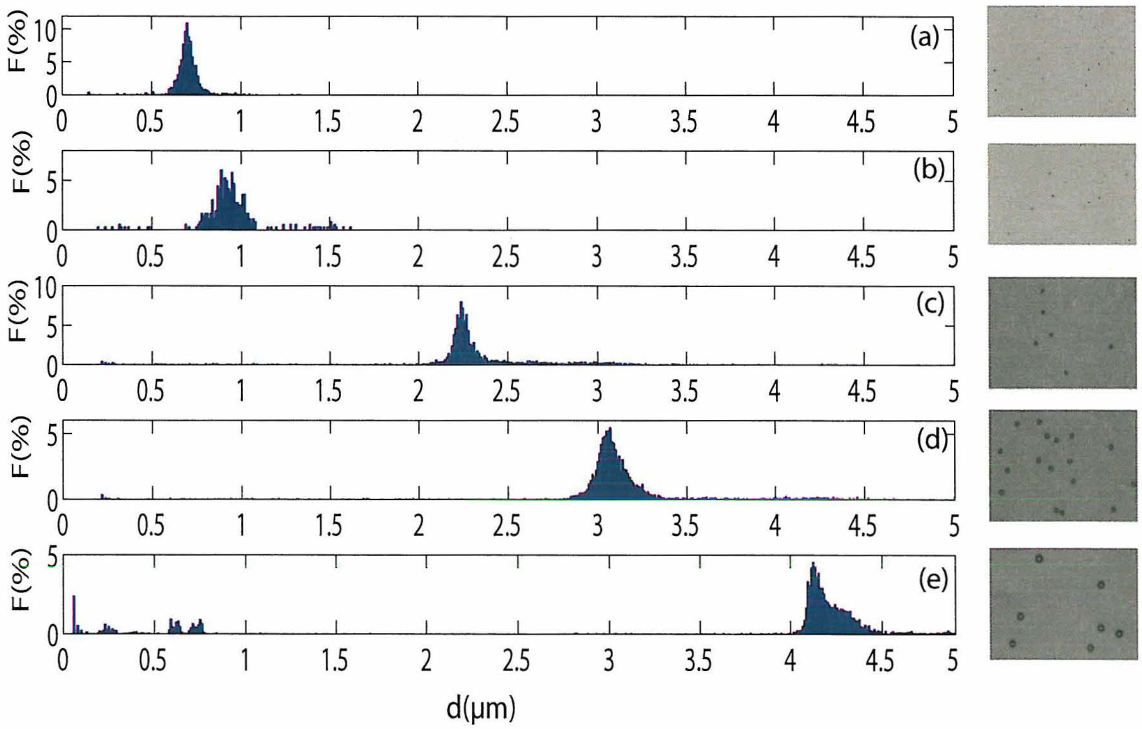


Figure 6 - Particle size distributions for the five particle solutions used. A sample grayscale image obtained using the microscope is included to the right of each distribution.

The ultrasonic generator used in the experiments was based on the design of Trinh (Trinh, 1985) and is illustrated in Figure 7. As shown in the figure, two aluminum disks were used to sandwich two piezoelectric lead-titanate-zirconate (PZT) disks. These disks were separated from each other by a thin copper disk, which served as an electrode. The aluminum transducer served as the other electrode. Using the dimensions presented in Figure 7, this transducer has a resonant frequency of f_r ~30 kHz. The transducer emits effectively at frequencies near this resonant value, and this is the approximate frequency used for the experiments presented herein. Accordingly, prior to these experiments, the system was tuned by first adjusting the frequency of the AC voltage applied to the transducer to attain f_r. This was done by attaching a piezoelectric sensor to the back of the transducer. This signal was monitored on an oscilloscope, and the frequency of the AC signal was tuned until the signal from the piezoelectric sensor reached a maximum, indicating that the transducer was vibrating at f_r.

Once f_r was attained, the distance between the tip of the transducer and the brass reflector plate L was tuned so that this distance was an integer number of half wavelengths, i.e.

$$L = n\,\lambda/2 \qquad (2)$$

where λ is the acoustic wave length obtained from:

$$\lambda = c/f \qquad (3)$$

and *c* is the sound speed. As shown in Figure 3, the transducer was mounted on a linear positioning stage (Velmex, A60) allowing for the adjustment of *L*. As a first approximation, the value of *L* needed for the desired number of nodes, *n* was obtained from equations (3) and (4) and was set using the linear positioning stage. However this distance is not precise since the local sound speed *c* is a necessarily estimated value based on the lab temperature and pressure which cannot be known exactly in the air space between the transducer and reflector. Accordingly, as a next step, the spray was turned on, and the gap distance was further tuned according to the behavior of the spray. If Eq. (3) is precisely satisfied, the fine water drops generated by the spray would not fall straight down in the chamber, but rather would accumulate in pressure nodes, indicating that a standing wave field had been attained and Eq. (3) had been satisfied.

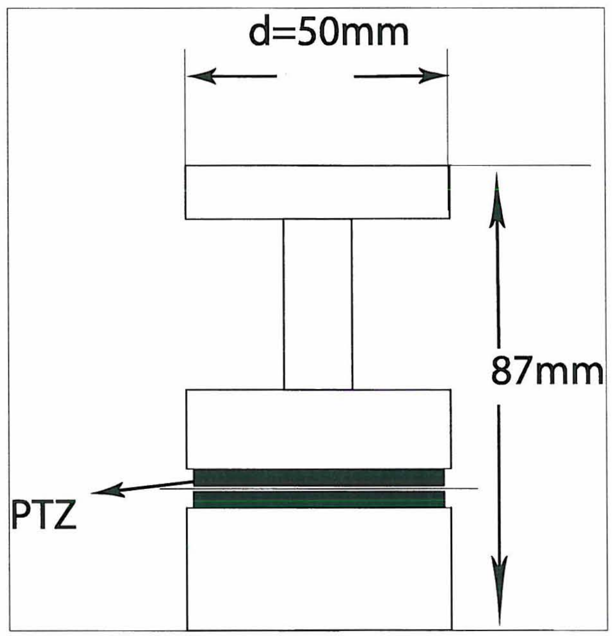


Figure 7 - Schematic of the ultrasonic transducer used in these experiments.

The amplitude of the AC voltage applied to the transducer was set to 90 volts. Higher voltages caused the transducer to overheat and become unstable.

Two identical Met One 237A particle counters (Hach Ultra Analytics Inc.) were used to measure the concentration of particles upstream and downstream of the scavenging chamber, as shown in Figure 2. The particle counters are capable of detecting particles larger than 0.5 um. Preliminary tests showed that for a PSL aerosol source, if the sampling tube lengths were equal for both counters, there was less than a 1% difference between the readings of the two particle counters. Because the particle counters are capable of detecting particles and water droplets, a diffusion dryer was placed between the scavenging chamber and the downstream particle counter to eliminate any liquid water from the flow, thereby ensuring that droplets were not sampled by the counter. For particles smaller than 1 micron there is negligible particle loss to the diffusion dryer. For particles larger than 1 micron, particle loss to the diffusion dryer is less than 20%. As will be demonstrated below, this loss is accounted for and does not affect the measured scavenging coefficients. The sampling rate for both particle counters was set to 5 sec/sample. Sampling from the two particle counters were synchronized to allow a simultaneous comparison of the particle concentration at the upstream and downstream locations, ensuring that measurement of *E* was not affected by drift in the particle generation rate.

Experimental procedure

Before each experiment, clean air was passed through the system until both particle counters attained a reading of zero. The air flow used in this experiment was obtained from the laboratory air compressor and was filtered by a 0.3 micron cutoff filter. Once the particle counters both read zero, the spray was turned on, and the downstream particle counter was monitored for 5 minutes to ensure that it remained at zero, thereby ensuring that droplets were evaporating prior to reaching that counter. Then the spray was turned off and the aerosol generator was turned on, and was allowed to run until both particle counters read a constant, stable value. Once this was achieved, particle concentration data acquisition began. During data acquisition, the scavenging chamber was operated in two modes. One mode was idle mode, where the water spray and the ultrasonic generator were both off. In this mode, any differences between the upstream and downstream particle counters are due solely to particle deposition in the lines (tube wall, diffusion dryer, etc.). The second mode was scavenging mode during which the water spray was turned on. Scavenging mode was run with and without energizing the ultrasonic transducer. In scavenging mode, the difference between the upstream and downstream particle counter readings is due to the combined effect of particle deposition in the lines and due to particle scavenging by the spray. During an experiment, these two modes were operated sequentially, each for 6 minutes, switching back and forth between the modes until the data storage buffer in the particle counters were full, which was typically 36 minutes. Once this occurred, the data was downloaded to a computer for subsequent analysis. This sequence was repeated five times for each run. Hence, for a given run, total data acquisition occurred for 180 minutes. Combined with the experimental preliminaries, each run lasted about 5 hours. This procedure was the same for experiments with or without the ultrasonics turned on.

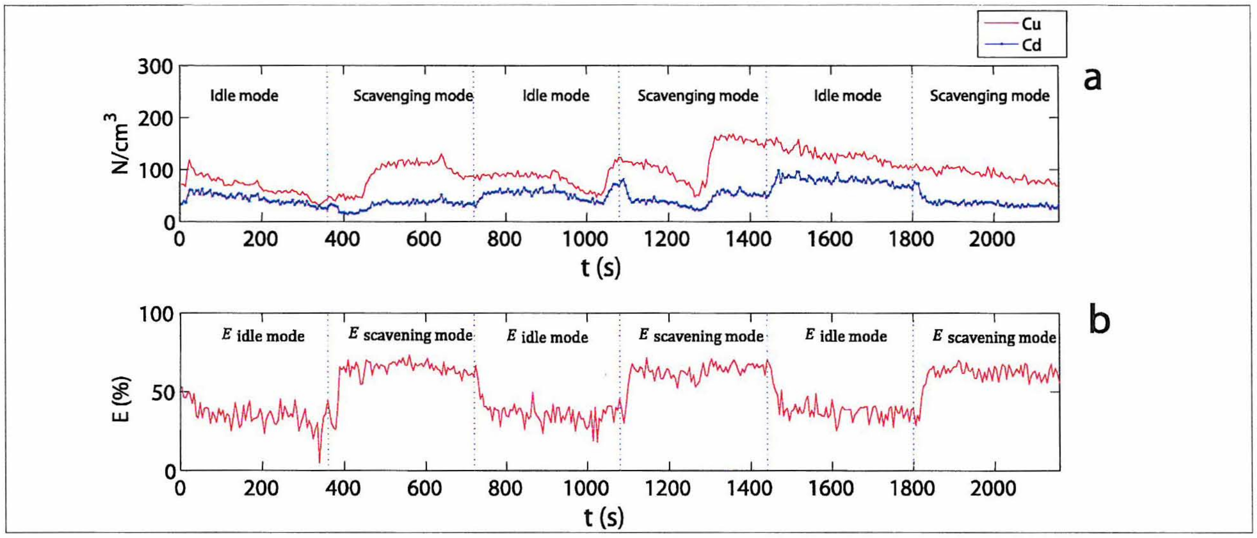


Figure 8 - (a) Particle concentration time traces from a sample experiment. (b)The time trace of E obtained by applying Eq. (1) to the data in (a).

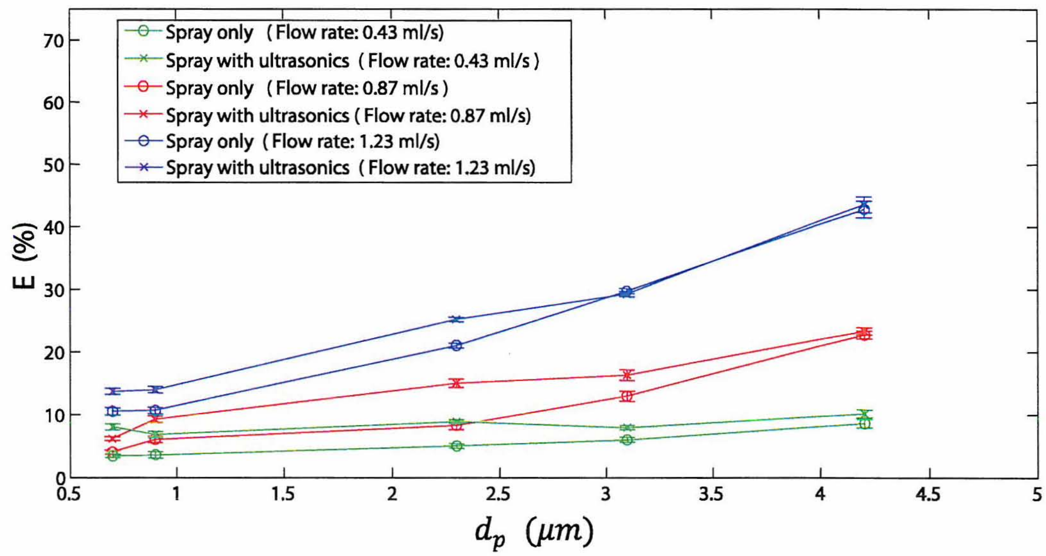
A sample time trace is presented in Figure 8 (a) showing the particle concentrations of the upstream particle counter C_u and the downstream particle counter C_d. The scavenging coefficient *E* is computed according to the equation:

$$E = \left(\frac{C_u - C_d}{C_u}\right)_2 - \left(\frac{C_u - C_d}{C_u}\right)_1 \qquad (5)$$

where the subscripts *1* and *2* in Eq. (5) refer to idle mode and scavenging mode, respectively. By subtracting the two terms in parentheses in Eq. (5), the effect of deposition of particles in the line is eliminated. Figure 8(b) is a plot of *E* obtained by applying Eq. (5) to the data of Figure 8(a).

Results

Figure 9 - Plot of scavenging coefficent versus particle diameter for three water spray flow rates. Results are presented with and without and ultrasonic standing wave field.



The main results of this work are presented in Figure 9 where the scavenging coefficient is plotted against particle diameter for the case where PSL spheres were used ranging from slightly more than 0.5 microns to slightly more than 4 microns in diameter. The particle diameter plotted in this figure is the average diameter, and the distribution for each of these diameters is presented in Figure 6. Each scavenging coefficient plotted in Figure 9 is the average scavenging coefficient calculated by Eq. (5) based on 1800 particle concentration samples taken in an experiment that lasted on the order of 5 hours. The error bars in the figure are the 95% confidence intervals of the average scavenging coefficient. The data is presented for three different spray flow rates: 0.429, 0.874, and 1.23 ml/sec, and the air flow rate was 50 cm^3/s. For each of the water spray flow rates, experiments are presented with and without the use of ultrasonics. Broadly speaking, Figure 9 shows that *E* increases with particle diameter and flow rate. Also, this plot shows that the scavenging coefficient is increased by the presence of an ultrasonic standing wave field. This is not as clear in Figure 9, but is better revealed in Figure 10 where the percent improvement in scavenging, *I* is plotted against particle diameter, where *I* is defined as:

$$I = \frac{Eu - Ew}{Ew} \times 100 \quad (6)$$

where E_u and E_w are the scavenging coefficients with and without ultrasonics, respectively. Figure 10 presents the same data as Figure 9, but with *E* replaced by *I*. This figure shows that the percent improvement in *E* due to ultrasonics is significant, and approaches 150% improvement when the flow rates are low and the particle diameter is small. This is significant since wet scrubbers currently perform poorly for small diameter particles. Also, the diameters where large improvement occurs are the diameters most threatening to the pulmonary health of mine workers.

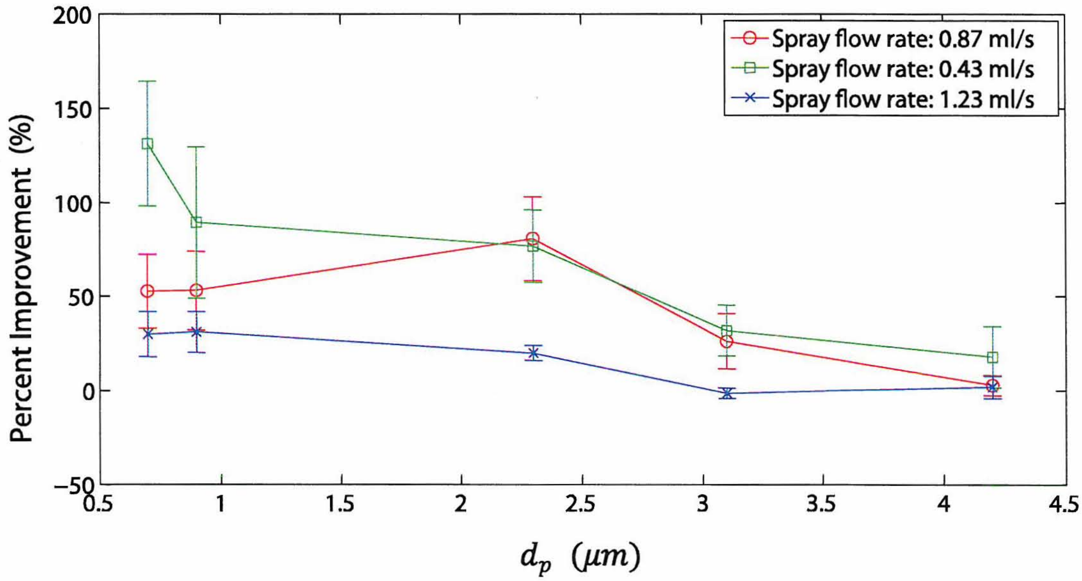


Figure 10 - Percent improvement in scavenging efficiency due to ultrasonics versus particle diameter, for the three spray water flow rates tested.

As noted earlier, experiments were conducted using PSL particles, and also using particles that existed in the ambient laboratory air environment.

Figure 11 is a presentation of the difference in scavenging coefficient for these two cases. Specifically, *E* is plotted against the spray water flow rate for the ambient air particles, whose average was 0.8 um, and for PSL particles for the 0.9 um case, which is the PSL diameter case closest to the average ambient air particle diameter. The distribution in particle diameters for the ambient air case is presented in Figure 12. In

Figure 11, the air flow rate was fixed at 50 cm^3/s, while the spray liquid flow rate was varied from 0.1 ml/s to 1.4 ml/s. Each point on the figure is the average scavenging coefficient calculated by Eq. (5) based on 1800 particle concentration samples taken during the course of an experiment lasting approximately 5 hours. The error bars in the figure are the 95% confidence intervals for each scavenging coefficient. For both particle types, the figure shows that at fixed water spray flow rate, there is a significant increase in scavenging coefficient in the presence of an ultrasonic standing wave field. The percent improvement due to ultrasonics, *I* (Eq. (6)) is presented in Figure 13, showing improvements approaching 150% for the ambient particles and approaching 100% for the 0.9 um PSL particles. This figure also shows that the scavenging coefficient is dependent on the type of particle used, all other quantities held constant. Specifically, Figure 13 shows that PSL particles were scavenged more readily than the ambient air particles. However, when combined with the large 95% confidence interval bars for the 0.9 um PSL particles in Figure 13, as well as the fact that the ambient air particles and PSL particles do differ slightly in diameter, this effect is not as strong as the others investigated here.

Figure 11- Scavenging coefficient versus liquid flow rate. Comparison of the effect of ultrasonics on scavenging for ambient air particles and PSL particles.

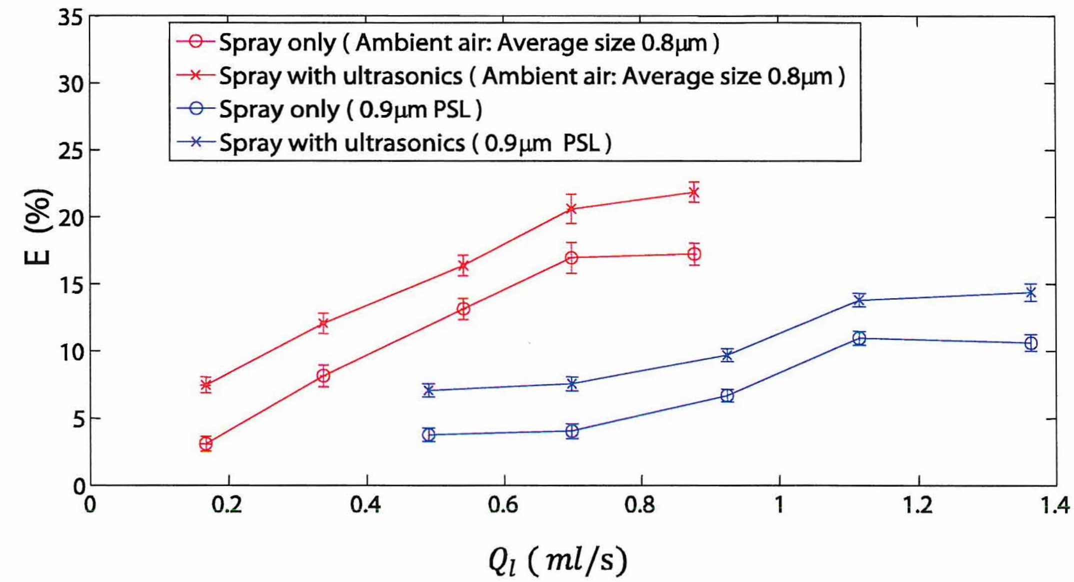
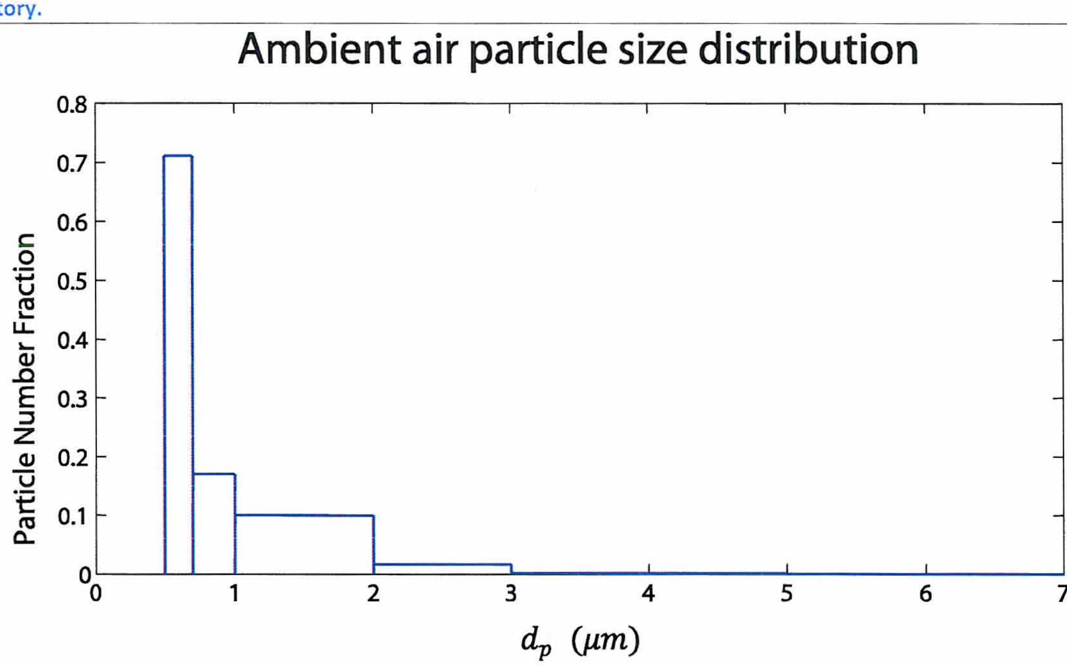


Figure 12 - Particle size distribution for ambient air particles in the laboratory.



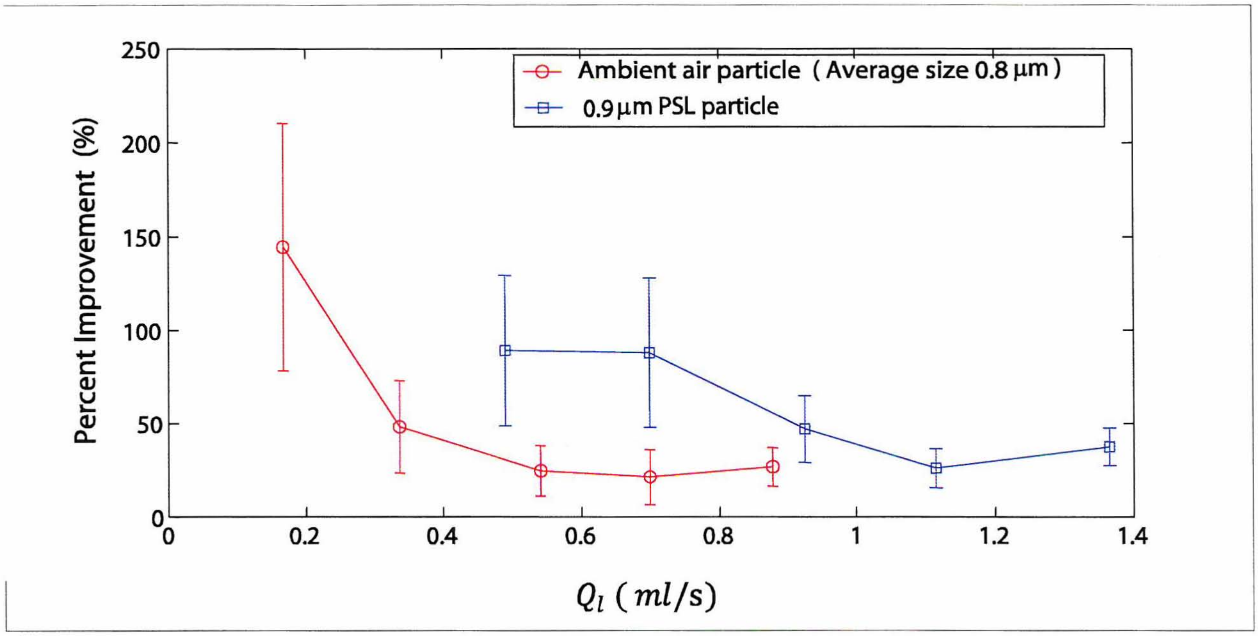


Figure 13 - Percent improvement in scavenging coefficient due to ultrasonics versus liquid flow for PSL particles and ambient air particles.

The second main aim or thrust of this research was to obtain an understanding of how drop oscillations and drop wakes affect particle scavenging. This was to be achieved via single drop studies where a single drop would be levitated by an ultrasonic transducer. A flow of particles was to be directed over the drop and the scavenging coefficient of that drop would be measured. This proved to be significantly more challenging than the multidrop study described above and more challenging than was anticipated. The primary reason for this was that the particle source that was required for this study was a vibrating orifice aerosol generator (VOAG) which failed to provide a stable, monodisperse particle size distribution. This created significant problems in the measurement of an accurate, reproducible scavenging coefficient for any set of conditions. Specifically, the VOAG created particles showing clear signs of doublets and triplets above the primary particle peak – that is, the PSDs had multiple peaks. This was not an insurmountable problem in that we developed a mathematical method to obtain scavenging coefficients as a function of particle diameter, even with this type of PSD. However what did create a problem that we are still struggling with is the fact that these multi-peak PSDs also drifted over relatively short periods of time. That is, the entire PSD would drift to higher or lower particle diameters over the course of minutes. This could potentially be addressed if a measurable number of particles are scavenged by the drop in this time interval. However, this has not been the case to date. We have been able to levitate single drops, flow fluorescein particles over them and measure the mass of fluorescein scavenged by the drop. We can do this with a stationary drop and with a drop oscillating in shape. However, we need to do these runs over approximately eight minutes in time and the diameters of the VOAG-created particles change during that time. Since this grant has ended, work in this direction has continued on an unfunded basis. Specifically, we are searching for methods to (i) stabilize the VOAG output and/or (ii) obtain measurements of E over very brief periods of time so that the variability in VOAG output does not affect the measurements.

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Publications:

Publications are in progress.