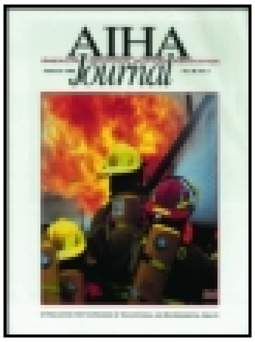

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Mist Control at a Machining Center, Part 1: Mist Characterization

AUTHORS
William A. Heitbrink[a]
John M. Yacher[c]
Gregory J. Deye[a]
Amy Beasley Spencer[b]

[a]U.S. Department of Health and Human Services, Public Health Service, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health, Division of Physical Sciences and Engineering, 4676 Columbia Parkway—R5, Cincinnati, OH 45226–1998;
[b]Presently with National Fire Prevention Association, 1 Batterymarch Park, Quincy, MA 02269
[c]Retired

At a machining center used to produce transmission parts, aerosol instrumentation was used to quantitatively study mist generation and to evaluate the performance of an air cleaner for controlling the mist. This machining center drilled and tapped holes at rotational speeds of 1000 to 3000 rpm. During most machining operations, the metalworking fluid (MWF) was flooded over the part. To facilitate metal chip removal during some operations, MWF was pumped through the orifices in some tools at a pressure of 800 psi. These machining operations were performed in a nearly complete enclosure that was exhausted to an air cleaner at a flow rate of 1.1 m^3/sec (2400 ft^3/m). Although the use of high-pressure MWF increased the mist concentration by about 200%, it did not affect the mist size distribution. The observed penetration through the air cleaner appeared to be mostly consistent with the manufacturer's specifications on the air cleaner's filters. During the testing, MWF was observed to accumulate in the bottom of the filter housing and may have been reentrained due to air motion or mechanical vibration.

Keywords: metalworking fluids, mist, machining operations

Health effects associated with metalworking fluid (MWF) exposures include dermatitis,(1) respiratory disease,(2) hypersensitivity pneumonitis,(3) and asthma.(4–7) Cross-shift decrements in lung function are reported for aerosol exposures larger than 0.2 mg/m^3 for particles smaller than 9.8 μm.(2) The respiratory health effects are attributed to the aerosol generated as a metalworking fluid (MWF) mist. Concerns about nonmalignant respiratory disease prompted the National Institute for Occupational Safety and Health (NIOSH) to state a recommended exposure limit of 0.4 mg/m^3 for the thoracic particulate, which is equivalent to a total particulate mass of 0.5 mg/m^3.(8) Some ongoing research has suggested that lifetime exposures to specific types of MWFs (straight, soluble, and synthetic) are associated with several digestive cancers.(9)

For the purposes of this and the associated article (*AIHAJ 61*:282–289), MWF mist is the liquid and solid aerosol present at machining operations. Typically, mist is defined as a liquid particle generated by either condensation or the mechanical shearing of the liquid.(10) To evaluate whether occupational exposure to MWF mist is acceptable in terms of the NIOSH recommended exposure limit, typically one measures the total or thoracic mass of aerosol present.

There is much exposure data on worker exposure to MWFs, which varies with the type of fluid, the machining operation, control measures employed, and indoor humidity.(11) Operator exposures at equipment with a ventilated original equipment manufacturers enclosure had a median exposure of 0.2 mg/m^3 and the exposures at retrofit and unenclosed machines, respectively, were 0.45 and 0.48 mg/m^3.(12) The difference between original ventilated equipment and retrofit/in enclosed equipment was statistically significant ($p < 0.0001$).

Frequently, occupational exposures to MWFs are controlled by ventilating an enclosure with an air cleaning unit that includes a fan preceded by several stages of filtration. To select an air cleaner with appropriate filtration characteristics, one must know the aerosol size distribution of the challenge aerosol and how the efficiency of the filters varies with aerosol size. Filtration efficiency data is generally available from manufacturers. When filters were used to collect MWFs,

Mention of company and/or product name does not constitute an endorsement by the Centers for Disease Control and Prevention.

filtration efficiency has been observed to degrade with time.[13] Data on the size distribution of MWF aerosols is scarce, and there was only one report on the size characteristics of machining aerosols in the industrial environment.[14] The reported aerosol distributions were polydisperse and varied with each operation. High shear stress/high temperature operations were associated with the production of aerosol smaller than 1 μm. Spraying and centrifuging were associated with the production of particles larger than 8 μm.

Mineral oils have a sufficient vapor pressure so that evaporation/condensation phenomena can occur.[15] This can lead to sample loss from filters and air samples.[16]

Because of the reported health effects, NIOSH researchers assisted an industrial partner in an effort to reduce worker exposure to MWFs by using air cleaners to control mist generated at automated enclosed machining centers. First, the aerosol generation at the air cleaner was characterized and the performance of the air cleaner was evaluated. This effort is the subject of the present article. Subsequently, air cleaners were installed on 25 machining centers. A second article reports on the effect of these control measures on MWF exposures was evaluated.[17]

FACILITY DESCRIPTION

In this plant, there were approximately 300 employees in the production area. Production occurred 24 hours a day, with most production area employees working a 10-hour shift, 40-hour week. Transmissions are produced for off-the-road vehicles such as lawn mowers and agricultural equipment. The iron castings that are brought into the plant are preshaped for transmissions. Additional metalworking is performed on the piece, including milling and drilling. Each metalworking station is automated, with one operator programing and tending several machines. Smoking was not permitted in this plant. The plant was air conditioned, maintaining a temperature of about 23°C and a relative humidity of 50%.

Machining was done in totally enclosed automated machining centers that, according to plant personnel, were the source of the mist exposures. Although these machining centers were enclosed, they were not ventilated. During machining operations MWF was used to remove metal shavings and to serve as a coolant and lubricant. At the metalworking station examined in this study, the MWF was flooded onto the part at a pressure of 550 kilopascals (kPa) (80 psi). During some machining operations, the MWF is forced through small holes in the drills at higher pressures ranging between 4134 to 6585 kPa (600 to 850 pounds per square inch [psi]). The high-pressure application of fluid was used during approximately 30% of the machining cycle, and this appeared to create much mist generation inside the enclosure. During the high-pressure application of MWF, the tooling rotations reached as high as 4500 rpm, with an average of 1000 rpm. The lower pressure applications flooded the part with the fluid at around 550 kPa during approximately 70% of the machining cycle. The bottom of the machining station had a sloped bottom where the excess fluid and debris were removed via a screw feeder leading to the fluid recycle system. The fluid flowed by gravity through covered flumes to a filtration unit. The returning fluid was filtered to remove metal chips and debris and stored in a pit that had a volume of 37.8 m^3 (10,000 gallons). The fluid was pumped from this pit to one of 12 machining centers. The fluid used in this system was Syntilo® 9902 (Castro Industrial, Inc., Downers Grove, Ill.), a synthetic product primarily composed of water and triethanolamine. The coolant concentration was maintained between 6–8% of the concentrate in water.

EXPERIMENTAL PROCEDURES

An in-plant trial of an air cleaner, which might be used to control mist generated at machining centers throughout this plant, provided an opportunity to study how machining operations affected mist generation and to evaluate the performance of the air cleaner. This was accomplished experimentally by using aerosol instrumentation to measure size-dependent mist concentration upstream and downstream of the air cleaner. The air cleaner (Model F120, Airflow Systems, Inc., Dallas, Tex.) was mounted on top of an adjacent machining center, as shown in Figure 1. The unit was installed over the metalworking station and pulled the air into the cleaning unit. The air cleaner's fan moved approximately 1.1 m^3/sec (2400 ft^3/min) of air through the enclosure, an elbow, and 4.5 m (15 feet) of 35-cm (14-inch) diameter duct that connected the air cleaner inlet to the enclosure.

The air cleaner, illustrated schematically in Figure 2, was equipped with a metal mesh prefilter, followed by a pleated "mist eliminator." Next were the main filters, which were 95% efficient American Society of Heating, Ventilating, and Air-Conditioning Engineers (ASHRAE) pocket filters. According to ASHRAE, a 95% efficiency filter removes all particles with a diameter of approximately 2 μm or larger. The efficiency curve of a 95% efficient ASHRAE filter also shows a minimal efficiency of approximately 72% for particles sized near 0.3 μm.[18] The fluids captured by the filters dripped to the floor of the cleaner and exited via three drainage holes. The MWF then drained to the MWF recycling system. The outlet of the air cleaner was a four-way adjustable grill for the exiting air.

The test stand shown in Figure 3 was used to draw an air sample into an air sampling chamber. The size-dependent mist concentrations were measured in the duct upstream of the air cleaner. The measuring position was approximately 1.2 m (4 feet) from the air cleaner's inlet and approximately 3 m from the elbow connecting the metalworking station's enclosure to the duct. Size-dependent mist concentrations were also measured at the exhaust louvers.

The test stand was designed and constructed for extracting an isokinetic sample from an exhaust duct. The air samples entered the chamber through a 1.3-cm diameter nozzle that expanded to an exit diameter of 3.8 cm in a horizontal distance of 9 cm. The nozzle was fabricated from 0.01-cm thick brass shim stock. After flowing into the nozzle, the air flowed into a 5.1-cm horizontal length of a copper tubing into copper elbow (3.8-cm diameter, 7.6-cm turning radius). The elbow was connected to a 134-cm length of 3.8-cm diameter copper tubing. This copper tubing extended 14 cm into the plastic column shown in Figure 3. The air flowed out of the copper tubing into a 15-cm diameter plastic column. In the column, the air flowed past a baffle, which mixed the air by inducing turbulence, and through a flow straightener. The inlets to the sampling instruments were located between the flow straightener and a perforated metal plate that served to evenly distribute the airflow for air sampling. Air was drawn through this test stand by a vacuum pump and other pumps associated with the instruments. To protect the vacuum pump, the air flowed out of the test chamber through a cartridge filter (Speedaire Part 62949, Dayton Electric Mfg. Co., Chicago, Ill.). The flow rate

FIGURE 1. Front of the machining center and the duct connecting the machining center enclosure and the air cleaner

was controlled by a rotameter equipped with a valve (Serial No. 096196, Cole Parmer, Niles, Ill.).

To collect an isokinetic sample from the duct upstream of the air cleaner, the average duct velocity and flow rate were determined by conducting a 10-point, equal area pitot tube traverse in the duct.[19] Based on the pitot tube traverse, the average velocity in the duct was 11 m/sec. Based on a probe diameter of 1.3 cm, a total flow rate of 85 L/min was used to achieve isokinetic sampling conditions. The total flow rate was the sum of the flow through the rotameter and instruments. A velometer (Velocicalc, TSI Inc., St. Paul, Minn.) was used to measure the air velocities at the outlet. The velometer showed that air velocities were between 10 and 12 m/sec at the air cleaner outlet. Therefore, the test stand flow remained at 85 L/min.

The sampling period started when the parts, which were mounted on a part holder called a "tombstone," entered the machining station. The sampling was terminated when the last machining operation stopped. For each sampling period, which lasted approximately 2 hours, a list of machine tools used was obtained from the programs used to operate the machining centers. There were two sampling periods for data collection upstream of the air cleaner and one sampling period for data collection at the air cleaners exit. This list noted whether high-pressure MWF was applied and what type of metalworking operation occurred. Each sampling period involved 37 or 38 distinct operations. The time for each step in the machining operation was recorded so that the

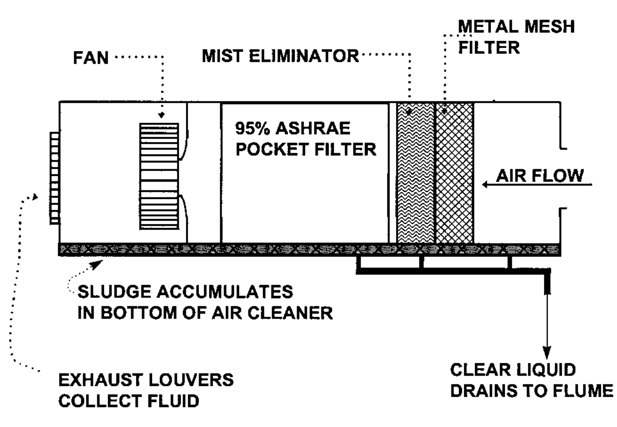

FIGURE 2. Schematic of installed air cleaner including qualitative observations of MWF accumulation on bottom of air cleaner

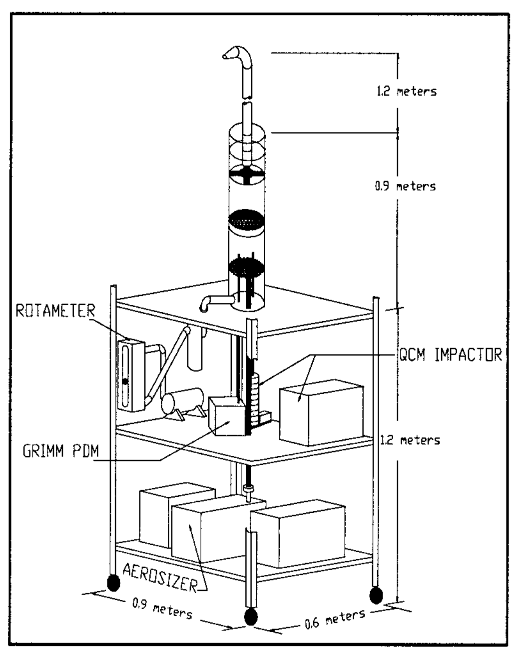

FIGURE 3. The test stand for extracting isokinetic samples from the duct and measuring the size distribution of the mist

APPLIED STUDIES

relationship between machining activity and mist generation could be studied.

Aerosol instrumentation was used to study the relationship between mist concentration and size distribution during distinct machining operations. The Portable Dust Monitor (PDM; Model 1.105, Grimm Labortechnick GmbH&Co, Ainring, Germany) was used to continuously monitor mist concentration. The PDM is an optical particle counter, which sampled through a 55-cm long, 0.6-cm diameter probe at a flow rate of 1.2 L/min. The PDM counts individual particles and classifies particles based on the amount of light scattered by the individual particle. For a series of sequential 6-sec periods, this instrument's RS-232 output lists time, data, and number of particles larger than 0.75, 1.0, 2, 3.5, 5, 7.5, 10, and 15 μm. This RS-232 output was recorded by operating a terminal program (Procom Plus, Datastorm Technologies, Columbia, Mo.) on a portable computer. The instrument and the data logging equipment were operated continuously throughout the data collection.

The Quartz Crystal Microbalance (QCM) Cascade Impactor (Model PC-2, California Measurements Inc, Sierra Madre, Calif.) was used to take short-term measurements of the mist particle size distribution and concentration. To obtain measurable quantities of mist, sample times were varied from 30 to 900 sec. The QCM draws 0.25 L/min of air from the column through a 30-cm length of a 0.96-cm inside diameter (i.d.) steel tube. In the QCM, the air flows through a series of progressively smaller jets, which forces the air to flow around piezoelectric crystals that serve as impaction targets and sensors for the mass collected after each impaction jet. The size of the aerosol collected on an impaction stage is determined by the efficiency of the impaction stage and the preceding impaction stage. The 50% cut diameter of the two impaction stages is customarily used to report the aerosol size collected on an impaction stage. The 50% cut diameter is the size at which 50% of the aerosol impacts on the impaction target. The experimentally determined values of the 50% impaction diameters obtained by Fairchild and Wheat were used to analyze the data.[20] These cut diameters are between 0.14 and 17μm. The sampling time was varied to collect measurable masses of aerosol on the impaction surfaces without overloading the piezoelectric crystals.

A time-of-flight aerosol spectrometer (Aerosizer Mach 2, Amherst Process Instruments, Hadley, Mass.) was used to obtain short-term size distribution measurements during selected operations. The Aerosizer was used with an Aero-diluter and a vacuum pump to draw 2 L/min through a 1.9-cm i.d. steel pipe through a preselector. In the Aerosizer, individual particles are sized based on their transit time between two laser beams. As particles pass through the two laser beams, scattered light is detected by two photo multiplier tubes. The time difference between these two events is measured. The two laser beams are located near the exit of an acceleration nozzle. The air exits this nozzle at near sonic velocity and continues to accelerate through the measuring region. Particles are accelerated by the drag forces generated by the accelerating airflow, which ultimately reaches a velocity of 500 m/sec. Such high velocities may deform or break the individual mist particles, causing errors in the measurement of concentration and size distribution. Liquid droplet deformation is reported in another time-of-flight aerosol spectrometer that operates at lower velocities.[21] To prevent artifact formation, an impactor was used as a preselector to eliminate particles whose breakup might cause anomalous results. The impactor had a 50% cut diameter of 14 μm. It had a 6-mm diameter jet, and it was the number two impaction stage of a cascade impactor (Sierra Series 260 Marple Impactors, Sierra Instruments, Carmel Valley, Calif.). This instrument provided particle size information over the range 0.3 to 14 μm.

The inlet diameters and inlet velocities used for the aerosol instruments were isoaxial but not isokinetic. The air velocity in the sampling chamber in Figure 3 was only 8 cm/sec. Formulas summarized by Brockman for isoaxial sampling were used to evaluate whether the anisokinetic sampling would affect results.[22] For the Aerosizer and QCM, deviations from isokinetic sampling conditions were estimated to cause less than a 5% error for particles smaller than 20 μm. For the PDM the aspiration efficiency for 20-μm particles was estimated to be 0.75 at 20 μm. Because the models assumed a turbulent flow in the sampling tube and flow in the PDM's sampling tube was laminar with a Reynolds number of 300, this available model might overstate line losses. Therefore, the data obtained from the Grimm PDM was not corrected for sampling efficiency.

RESULTS

The digital output of the Aerosizer and the PDM is number concentration. The product of number concentrations in each channel (C_j) and the mass per particle were summed over n channels to compute the mass concentration (C_m) of MWF mist. The mass per particle was computed using root mean diameter (d) and assuming unit density ($\rho = 1$ g/cm^3). The following formula was used to compute C_m:

$$C_m = \sum_{i=1}^{n} \left[\frac{\pi d_i^3 \rho}{6}\right] C_j$$

The mist concentrations measured by the Grimm PDM were analyzed to evaluate the effect of the following operations on mist generation: background (no machining), grinding without coolant, the application of low-pressure coolant, and the use of both low- and high-pressure coolant. Figure 4 is a plot of concentration measured by the Grimm PDM as a function of time during one of the production cycles. This plot shows the time interval during which each activity occurred. For each 6-sec concentration measurement, the activity occurring during the machining operation was one of the four activities described in the previous sentence. These activities continued for intervals of at least 1.5 min before the concentration changed. An average concentration was computed for the time that the activity occurred without change. This average concentration and activity were recorded in a second file. This second file was a sequential list of records containing a code describing the activity and average Grimm concentration during the activity. Before statistical analysis, the logarithms of the concentrations were taken. The SAS General Linear Models Procedure was used to conduct a one-way analysis of variance.[23] Machining activity significantly affected concentrations ($p < 0.0001$). A multiple comparison test, Tukey's Studentized Range (HSD), was conducted at an overall level of confidence of 95% to evaluate concentration differences among the different activities. These results are presented in Table I. The difference between the mean concentration listed in Table I and observed concentration is termed the "residual." The residuals from this analysis did not differ significantly from a normal distribution ($p = 0.1$).

Because the data from the Grimm PDM is a sequential list of concentrations, these concentration measurements may not be independent of each other.[24] To evaluate the independence of the measurements, the relation between the residuals and the residual for the previous observed value of concentration was evaluated.[25]

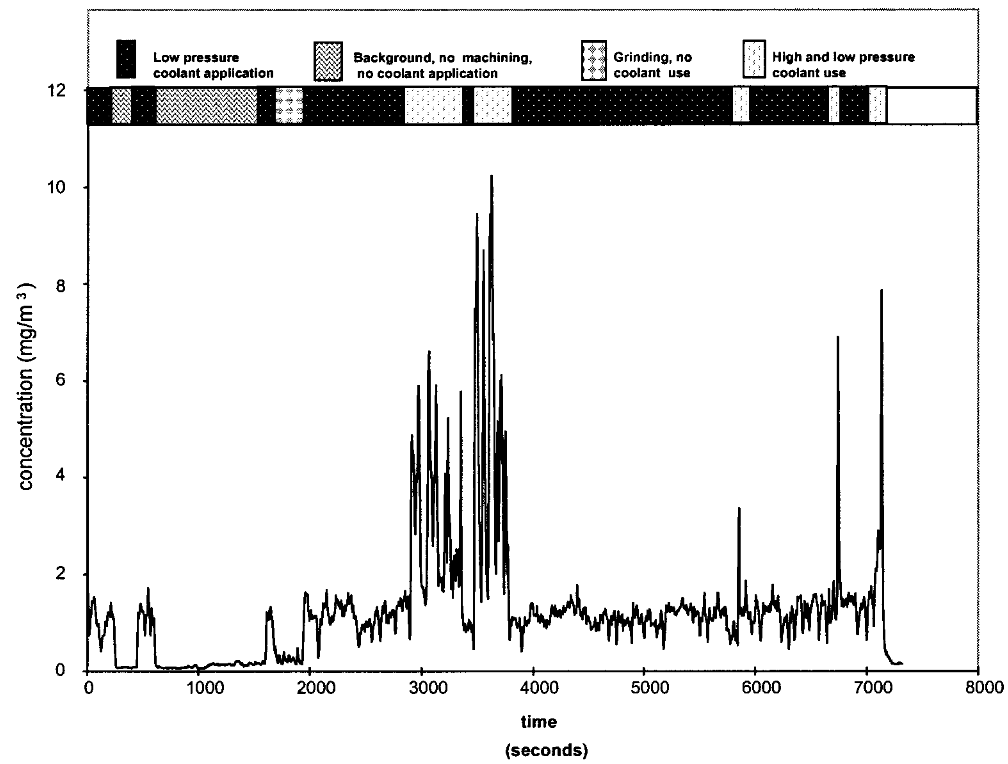

FIGURE 4. Mist concentration, measured by the Grimm PDM, upstream of the air cleaner

The latter value is termed the "residual at a lag of 1." Regression analysis was done to model the residual as a linear function of the residual at a lag of 1. The regression coefficient for the residual at a lag of 1 was 0.04 $\pm$ 0.19. Consequently, these measurements were concluded to be independent of each other.

Time series analysis was used to evaluate the Grimm concentration measurements made at the exit of the air cleaner. Data analysis was performed on the logarithms of the concentration measurements. The SAS Autoregression Procedure (SAS version 6.12, SAS Institute, Cary N.C.) was used to evaluate whether the machining activity affected the mist concentration.[26] The model adjusts for autocorrelation by allowing for autoregressive modeling of the residuals. The selected model allowed for autoregressive parameters involving seven time lags. After seven time lags, the autocorrelation was no longer significant. The geometric standard deviation estimated from the mean square error of the model was 1.12 with 832 degrees of freedom. Machining activities that occurred upstream of the filter and that are listed in Table I did not affect mist concentration ($p > 0.4$). The upper 95% confidence limit on the geometric mean concentration at the discharge of the air cleaner was 0.033 mg/m³. This upper confidence limit was significantly less than the background concentration reported in Table I ($p = 0.0002$). This concentration is an order of magnitude lower than the concentrations reported in Table I.

Figures 5 and 6 present size distributions measured with the Aerosizer and the QCM. In these plots, the term "$\Delta C_m/\Delta \ln(d_p)$" is plotted as a function of particle size. The mass concentration between two particle sizes is denoted as "ΔC_m." To compare measurements made by different instruments that have different channel widths, this concentration is divided by the difference in the natural logarithms of the particle diameters, which is termed "$\Delta \ln(d_p)$."

Figure 6 compares size distributions measured downstream of the air cleaner with a weighted average of size distributions measured upstream of the air cleaner. Because upstream and downstream measurements were not made at the same time, a weighted average distribution was computed for the aerosol entering the air cleaner. This average was weighted to reflect the fraction of the

TABLE I. Geometric Mean Mist Concentrations as Measured by the Grimm Portable Dust Monitor Upstream of Air Cleaner

Operation	Geometric Mean (mg/m³)	n	Grouping Code[A]
High-pressure coolant	2.97	11	A
Low-pressure coolant	1.34	3	B
Grinding	0.21	2	C
Background	0.2	4	C

[A]Geometric means with different grouping codes differ significantly.

TABLE II. Mass Median Aerodynamic Sizes

	Mass Median Diameters (μm)		
	Grimm PDM	QCM Impactor	Aerosizer
High- and low-pressure coolant application	4.1	5.4	5.1
Low-pressure coolant application	4.2	5.1	5.1
Grinding	2.5	not measured	2.8
Background	2.5	not measured	3.7
Exhaust from air cleaner	1.8	1.8	2

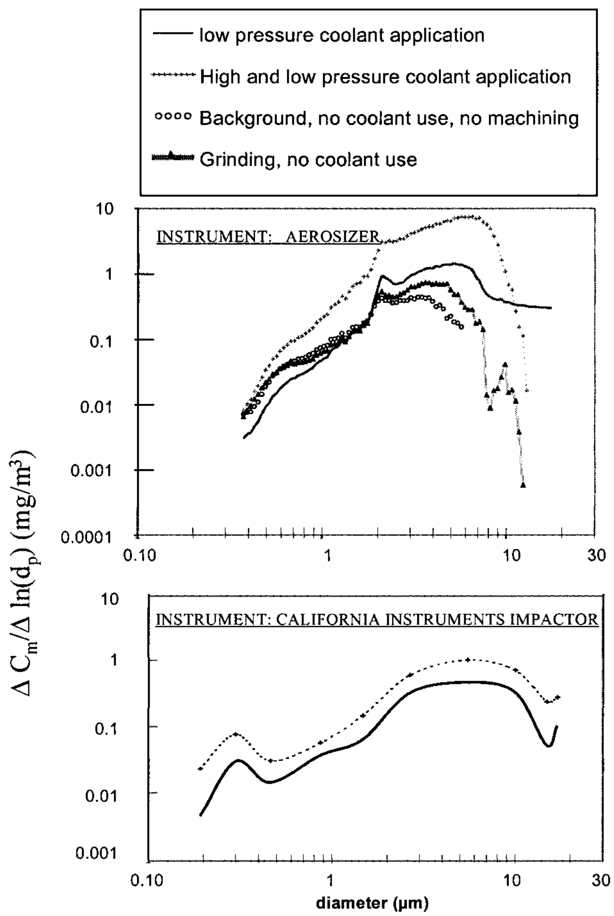

FIGURE 5. The size distribution of the aerosol entering the air cleaner. Machining operation and MWF application pressure affected the amount of mist generation without affecting the shape of the size distribution.

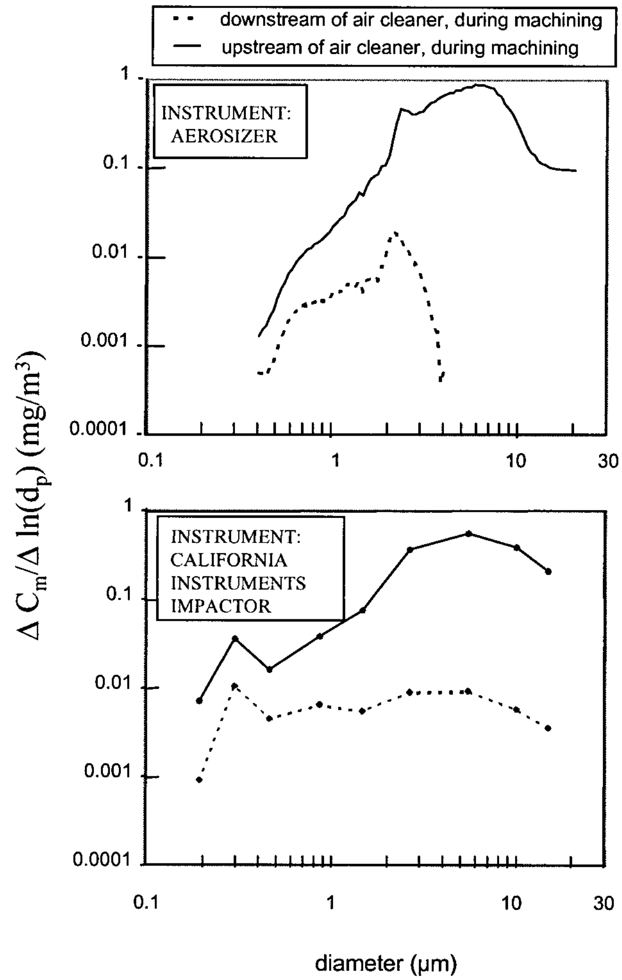

FIGURE 6. Size distributions upstream and downstream of air cleaner. As discussed in the text, the distribution upsteam of the air cleaner is a weighted average.

time that the following machining operations were done while the measurements were made downstream of the air cleaner: (1) machining without MWF, (2) applying MWF at low pressure, and (3) applying MWF at both high and low pressure.

After two months of operation, the outlet louvers of the air cleaner were coated with MWF, and MWF would occasionally spurt or drip out from the louvers. When the air cleaner was dismantled, drainage problems were found. The three small drains were clogged with debris, including metal shavings. These accumulations are illustrated in Figure 2. There was about a 1.5-cm depth of standing MWF in the base of the air cleaner. Apparently, this was the source of the large mist droplets that the air cleaner was observed to "spit." After the drains were enlarged and the air cleaner was tilted slightly toward the drains, the air cleaner's drainage improved and it ceased "spitting" droplets onto adjacent equipment.

DISCUSSION

Table I shows that the MWF concentration increased by a factor of two to four when the high-pressure MWF was used. As shown in Figure 4, the instantaneous peaks associated with high-pressure MWF use are as much as a factor of 10 higher than the mist concentration associated with the low-pressure MWF. The high-pressure coolant was generally used to flush chips from relatively deep holes. The MWF flowed out of a small orifice at the drill bit's cutting face. The high-pressure MWF flow started before the tool was inserted into the part, and this caused the immediate concentration peaks. As noted in a discussion of Bernoulli's equation as a steady state macroscopic energy balance, the fluid's mechanical energy involves both the fluid's kinetic energy and pressure.[27] When the tool was far enough into the part, the MWF's mechanical energy was dissipated by flowing out of the part, the MWF exited the part as a fluid stream, and the additional mist generation associated with use of high-pressure MWF decreased. Consequently, the peak concentrations were somewhat higher than the average concentration during the applications.

Although the application of high-pressure MWF increased the mist concentration, it did not greatly affect the shape of the size distribution presented in Figure 5. This is somewhat surprising, as increased fluid velocity is usually associated with decreased mist size.[28,29]

The results obtained from the Aerosizer, which are presented in Figure 6, indicate that the air cleaner removed particles larger than 4 μm. However, the QCM impactor results indicate that there are particles larger than 4 μm measured in the air flowing out of the air cleaner. In the Aerosizer, the number of particles counted is the difference between observed number of particles and background noise. Quite possibly, the counts of few large particles would be lost in this noise. At the air cleaner's exhaust, particles larger than 4 μm were measured by the Grimm PDM and the QCM impactor. When one of the authors inspected the exhaust grates of the air cleaner, mist droplets impacted on his safety glasses. These mist droplets were about 0.1 cm in diameter. These droplets landed on adjacent equipment, discolored the paint on this equipment, and annoyed plant personnel. Apparently, the liquid pool, which had collected due to the clogged drains, was a source of some mist emissions. Because the mist concentration at the outlet to the air cleaner was much lower than the background concentration, the installation of the air cleaner should reduce the MWF mist concentration in the plant. In the accompanying article, the effect of air cleaner installation on mist concentration in the plant is evaluated.

CONCLUSIONS

At the operation studied, mist generation appeared to depend on MWF application velocity. When the MWF flow started, mist generation started. When high-pressure MWF was used, mist generation increased. Mist generation did not appear to change with any one of the nearly 40 different machining operations. Mist size distribution did not appear to be affected by the MWF's application pressure.

The available data demonstrated that the air cleaner was effective in reducing the concentration of aerosol. The air cleaner removed most aerosols greater than 4 μm, which accounted for 90% of the aerosol's mass. However, the air cleaner did appear to be a source of some mist generation. Drainage from the air cleaner was observed to be a problem, causing the air cleaner to become a noticeable and annoying source of coarse mist droplets that discolored the paint on nearby equipment. This problem was fixed by improving the drainage from the air cleaner. As part of a routine maintenance program for these air cleaners, the drainage in the air cleaners is inspected and maintained. The preventive maintenance is conducted to prevent the air cleaner from becoming a source of mist emissions.

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