A Pilot Study of Mist Generation at a Machining Center*

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ABSTRACT

The control of occupational exposure to metal removal fluids generally involves enclosing the machining center and exhausting this enclosure to an air cleaner thant collects the mist before the air is recirculated to the workplace. In order to select an appropriate air cleaner, the size and generation rate of the mists needs to be known. In this study, mist size and generation rate were measured as a function of tool speed, fluid flow rate, and cutting rate at an enclosed machining center. A vertical machining center (Lancer™, Cincinnati Milacron) was totally enclosed and the air from this enclosure was exhausted through a 25-cm diameter duct to an air cleaner. Air samples were collected isoaxially from the duct and these instruments were used to measure mist concentration: a time-of-flight aerosol spectrometer (APS Model 3310, TSI, St. Paul, Minnesota), an eight-channel optical particle counter (Portable Dust Monitor Model 1.105, Grimm, Ainring, Germany), a cascade impactor (Micro-Orifice Uniform Deposit Impactor, MSP Corporation, Minneapolis, Minnesota), and an aerosol photometer (RAM, MIE, Bedford, Massachusetts). Data analysis was based on the measurements made with the cascade impactor and the time-of-flight aerosol spectrometer. The machining operation studied involved face milling a 30 x 31 cm square piece of aluminum with a 10-cm diameter face mill. Machining parameters were varied as a 2 x 2 x 3 factorial experiment with these variables: coolant velocity at constant flow rate (16.6 and 4.4 m/sec), tool speed (2,000 and 4,000 fpm), and metal removal rate (no removal, 2 teeth on mill, and 6 teeth on mill). An ANOVA was performed using the SAS's General Linear Models Procedure. The following variables significantly affected mist generation: fluid velocity, tool speed (rpm), and the interaction between tool speed and fluid velocity. When the fluid was applied over a stationary face mill, the higher fluid velocity resulted in a mist concentration that was a factor of 3 higher than the low fluid velocity. When the face mill cutters are moving at 2000 fpm (1,910 rpm), the mist generation increases by factor of 2 over the mist generation that is created by the application of the metal removal fluid at 18 m/sec over a stationary face mill. Increasing the face mill speed to 4000 fpm (3820 rpm) from 2000 fpm increases the mist concentration by a factor of 2-3. The results suggest that mist generation is largely a function of fluid motion, regardless of the energy source. When the fluid is turned on and exceeds some undetermined threshold velocity, mist generation starts. When the tool starts turning, the increased mist generation exceeds the concentration of mist generated by the fluid's application velocity. The actual metal cutting did not appear to affect the mist generation.

BACKGROUND

The occupational health literature contains reports associating occupational exposure to metal removal fluids (MRFs) with respiratory disease and cancer.[1, 2, 3, 4] Microbial contamination and endotoxins (debris from dead microbes) have also been postulated as potential causes of adverse pulmonary health effects.[1] Some on-going research has suggested that lifetime exposures to specific types of metalworking fluids (straight, soluble, and synthetic) are associated with digestive tract cancers.[3] For these reasons, controlling worker exposure to metal removal fluid is prudent.

MRF mists are generated at automated enclosed machining operations and at other less automated operations that cannot be tightly enclosed. The air exhausted from ventilated enclosures is processed by air cleaners and may be discharged back into the workplace. Selecting an appropriate air cleaner requires knowledge of the mist's concentration, size distribution, and

* This paper was unable to be presented at the Symposium, but is included here for completeness of these proceedings.

emission rate. Furthermore, knowledge of factors affecting mist emissions may allow conditions to be selected to minimize mist generation and worker exposure. To develop information needed to control occupational exposure to airborne MRFs, GM and NIOSH researchers are jointly investigating the effect of machining parameters upon MRF aerosol formation.

EXPERIMENTAL PROCEDURES

Mist generation at a machining center can be thought of as a three-step process with mist generation increasing during each step: 1) The fluid flow starts flowing over a stationary tool, 2) The tool starts rotating and mist generation is increased, and 3) The tool cuts metal. This model is useful in that it allows one to dissect the mist generation process during machining and to obtain some insight as to which processes are important. Thus, an experiment was conducted to evaluate the effect of fluid application velocity, tool speed (rpm), and metal removal rate upon mist generation.

The experiment was conducted at a Lancer™ Vertical Machining Center shown schematically in Figure 1. The machining center, was almost totally enclosed and 0.25 m^3/sec (540 cfm) of air was exhausted from the enclosure. The gap between the bottom of the enclosure and the coolant reservoir was sealed with duct tape to prevent mist leakage. During preliminary testing, an aerosol photometer was used to identify leakage at this point. The metal removal fluid was a typical soluble oil at a nominal concentration of 7%. The fluid's kinematic viscosity was 1.2 centistokes and its surface tension was 30-33.9 dynes/cm.

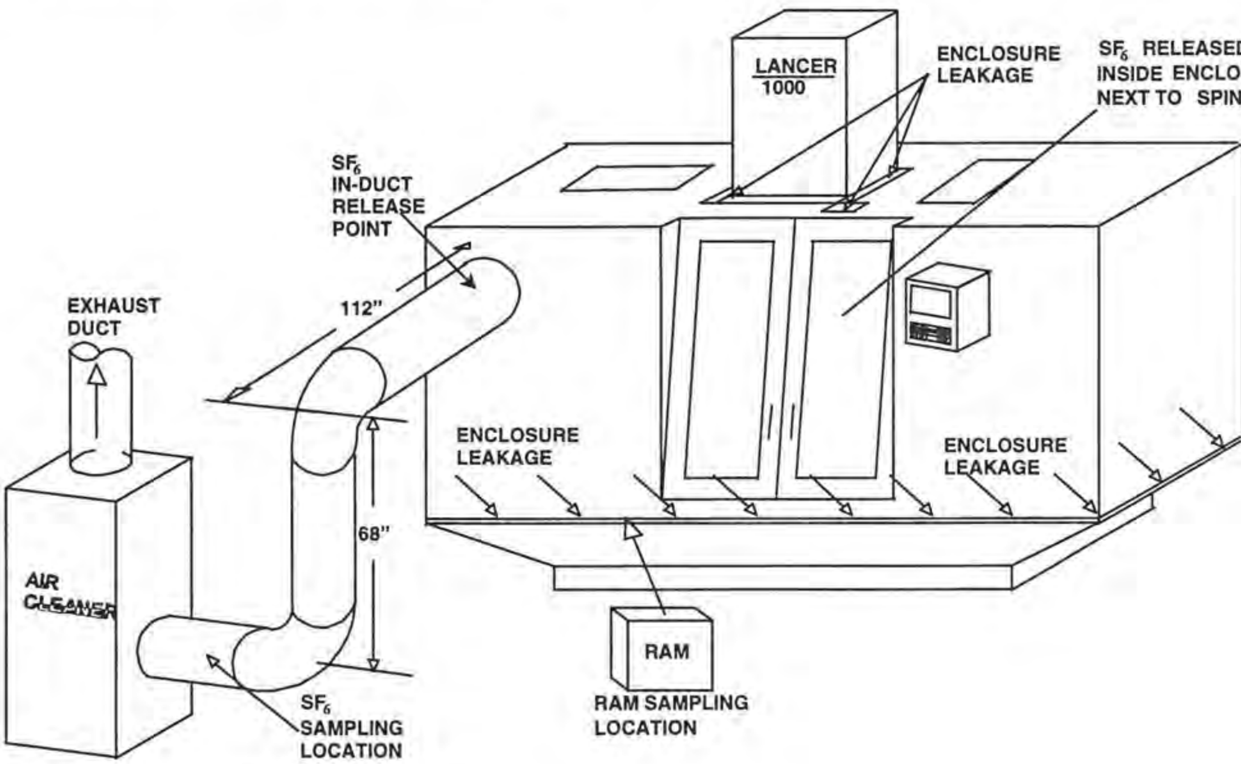


Figure 1. Schematic of machining center.

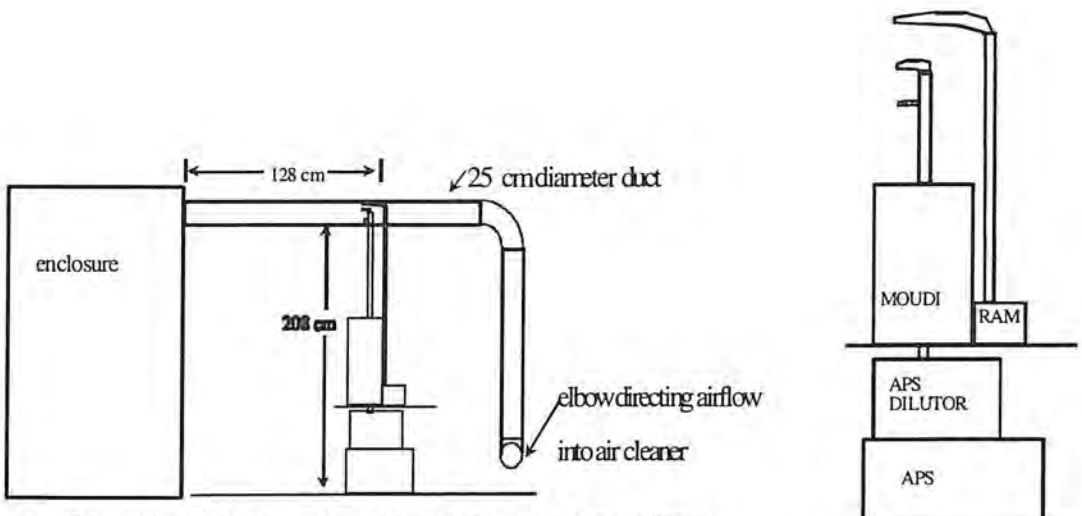
Face milling of a 30.5 by 31 cm rectangular surface of 2-cm-thick aluminum stock was used to study mist generation. This stock was drilled with a pattern of equally spaced holes to produce "interrupted cut" milling. The 0.6 cm diameter holes were 1.2 cm deep and arranged in a pattern of 16 columns of 15 equally spaced holes along the 31-cm length of the aluminum. This aluminum stock was clamped to the machining center's moveable worktable. A face mill with provisions for six carbide inserts was used to remove 0.04 cm of aluminum from the surface of the plate during each pass. The feed rate of the table was adjusted to obtain a constant feed of 0.01 cm/tooth regardless of tool speed or number of cutters. This face mill had a diameter of 10 cm and the mill's cutters were located on a circle 10 cm in diameter.

The experiment, which was conducted to evaluate the effect of the three machining parameters upon the mist concentration and size distribution, was organized as a 2 x 2 x 3 factorial experiment with two extra test conditions. The experimental parameters and their levels were as follows: 1) Fluid Application Velocity: 4.4 or 16.6 m/sec at a constant flow rate, 2) Tool speed: 2000 or 4000 sfm (1,910 or 3,820 rpm), and 3) Metal removal rate: null, 2 mill teeth, or 6 mill teeth. This experimental design produces five metal removal rates. Metal was not cut during the null condition; the spinning face mill with 6 mill teeth was positioned 0.003 to 0.007 cm above the part.

All possible combinations of these variables were tested. For the two extra test conditions, the fluid flowed over a stationary face mill at the two velocities listed above. This experiment involved 14 combinations of test conditions with one replication. Within each replication, the test conditions were run in random order. Every 4-6 runs, background particulate concentrations were measured for periods of 5-20 minutes. During background measurements, machining did not occur.

Each experimental run lasted 23 minutes. During the first three minutes, the concentrations were allowed to reach steady state. Preliminary experimental measurements made with an aerosol photometer indicated that mist concentrations required less than three minutes to reach steady state. After three minutes elapsed, data was collected for twenty minutes.

Based upon tracer gas results that were reported elsewhere, the air cleaner fan drew 0.25 m^3/sec of air into the enclosure, through a 25 cm diameter duct, past isoaxial sampling probes, and through a 97% DOP filter before discharging the air back into the facility. This was within 5 % of the design flow rate required for isokinetic sampling. As shown in Figure 2, the isoaxial sampling probes were used to transport air samples from the duct to instruments that were used to measure aerosol concentration. The sampling probe nozzles were fabricated from 0.01 cm thick brass shim stock. For each instrument, air entered the probe's nozzle that expands to the diameter of the tubing in a distance of 10 cm. After entering the nozzle, the air flowed into a 5 cm horizontal length of copper tubing, through a copper elbow and through another straight run of copper tubing. The tubing was common copper pipe and the elbows for the tubing had a radius of 2R. The diameters of the sampling probes and the sample tubes for each instrument are given in Table 1.



A. Exhaust duct which transports mist-ladden air past sampling equipment

B. Arrangement of air sampling equipment.

Figure 2. Schematic illustration of the sampling equipment

Table 1. Inlet Diameters and Velocities for Duct Sampling Probes

Instrument	Sample Tube Diameter (cm)	Inlet Diameter (cm)	Flow Rate (lpm)	Velocity (cm/sec)
APS	1.91	0.46	5	508
RAM	1.27	0.32	2	421
Grimm PDM	1.91	0.76	14	512
MOUDI 1	2.54	1.14	30	1487

The Following Instruments Were Used to Measure Mist Concentration:

The Portable Dust Monitor (PDM) (Model 1.105, Grimm Labortechnick GmbH & Co, Ainring, Germany). The PDM is an optical particle counter and has a flow rate of 1.2 liters per minute. The PDM counts individual particles and classifies particles based upon the amount of light scattered by the individual particle. The instrument's software records a series of consecutive 6-second particle counts in the following size channels: number of particles larger than 0.75, 1.0, 2, 3.5, 5, 7.5, 10, 15 µm as a function of time. This instrument was preceded with an impactor to eliminate particles larger than 15 micrometers.

The Aerodynamic Particle Sizer (APS model 33b, TSI, St. Paul MN) was used with an APS Diluter (model 3302, St. Paul NM). In the APS, individual particles are sized based upon their transit time between two laser beams. As particles pass through the two laser beams, scattered light is detected by two photomultiplier tubes. The time difference between these two events is measured. The Diluter was positioned on top of the APS as described in the instrument's operating instructions. A dilution ratio of 20 to 1 was used and the data was adjusted using the manufacturer's correction for the particle transmission efficiency of the diluter.

The Real-time Aerosol Monitor (RAM, MIE Inc, New Bedford MA). The RAM-1 continuously sampled the air from the side of the air sampling plenum as shown in Figure 2. The RAM- 1 was operated on the 0-2 mg/m^3 range and at a time constant of 2 seconds. In the instrument's sensing chamber, the RAM measures the quantity of light scattered by the entire cloud. The quantity of scattered light is a function of concentration and the aerosol's optical properties. Thus, this instrument's response is a measure of relative concentration. The analog output of this instrument was recorded every 10 seconds using a data logger (Ranger 11, Rustrack, East Greenwich, RI).

The Microorifice Uniform Deposit Impactor (MOUDI) (model 100, MSP Corporation, Minneapolis MN). This is an 8-stage cascade impactors that was operated at a flow rate of 30 lpm. This impactor is unique in that each stage rotates allowing the collected material to be uniformly deposited on the collection substrate. The metal removal fluid mist was collected on 37 mm, 5 µm pore size PVC filters (SKC Inc, 84 PA). The 50% cut diameters for this impactor are: 18, 10, 6.2, 3.2, 1.8, 1.0, 0.32, and 0.18 µm. These filters were pre- and post-weighed in a temperature- and humidity-controlled environment on an electrobalance readable to 0.001mg. The collected filter masses were adjusted for the weight change of the blank filters.

Temperature, relative humidity, and dew point were measured. Temperature and relative humidity were measured with a temperature and relative humidity probe (RR2-252 Rustrak Instruments, East Greenwhich RI). The dew point was measured with a chilled-mirror dew-point monitor (Model 911, EG&G, Walther Mas). The analog outputs of the RAMs, the temperature and relative humidity probe, and the dew point meter were recorded every 10 seconds with a multichannel data logger (Ranger II, Rustrak Instruments, East Greenwhich RI).

RESULTS AND FINDINGS

The APS's detection logic can cause the creation of spurious counts that have been termed phantom particles.[5] The APS count data was adjusted for phantom particle creation using a procedure that has been described earlier. In addition, the number of counts was adjusted by using the transmission efficiency for the APS diluter. The number concentrations (C_n) were used to compute the mass concentration (C_m) of the metalworking fluid mist using the channel's diameter (d), and assuming unit density (ρ), with n denoting the number of channels. The following formula was used to compute C_m:

$$C_m = \sum_{i=1}^{n} [n d_i^3 \rho/6]\, C_n \qquad (1)$$

The mass concentrations measured by the MOUDI were adjusted for reported inlet losses.[6]

Size Distribution

The mass fraction of material collected on each impaction stage and in each APS channel was computed. Because these mass fractions are probably dependent on each other, a multivariate analysis was used to evaluate whether test conditions affected the mass fraction in a size range. In the analysis of the MOUDI impactor data, the dependent variables in the statistical model were the mass fraction collected on each stage for stages 0 to 3. Approximately 80-90% of the mass was collected on these stages. The remaining stages were excluded because of concerns over analytical error. Multivariate Analysis of Variance was conducted to evaluate whether these mass fractions were significantly affected by the independent variables.[7] For each variable, a multivariate F test, Wilk's Lambda, was used to evaluate whether chance alone could have caused the observed differences in mass fraction. Because a full analysis of the data showed that the variables involving metal cutting did not affect the dependent variables ($p>0.05$),

Table 2 presents results of an analysis conducted to evaluate whether fluid velocity and tool rpm affected the mass fraction of material collected on stages 0-3 ($p < 0.005$). Before these statistical techniques were applied to the APS data, the mass fraction of material collected in the size ranges approximately corresponding to impactor stages 1, 2, and 3 of the MOUDI impactor were computed. The third column of Table 2 presents this analysis. The high probabilities indicate that fluid velocity and metal cutting conditions do not affect the shape of the size distribution measured by the APS. Tool speed did affect the shape of the size distribution ($p = 0.01$).

Table 2. Probability (Probability > F) that chance caused observed differences in the dependent variables.

Purpose	Evaluate whether independent variables affected shape of aerosol distribution		Evaluate whether independent variables affected amount of mist produced	
Type of Analysis	Multivariable Analysis of Variance		Analysis of Variance	
Dependent Variable	Mass Fraction on Stages 0-3 of MOUDI	Size Distribution APS	MOUDI Mass Concentration	APS Mass Concentration
Fluid Velocity (FV)	0.0047	0.22	0.0001	0.0001
Tool Speed (TS)	0.0001	0.01	0.0001	0.0001
FV * TS	0.0001	0.41	0.0001	0.001

Probabilities less than 0.05 indicate that the independent variable had a significant affect upon mist concentration.

Figures 3 and 4 graphically present the effect of tool speed and fluid application velocity upon the shape of the measured size distribution. The ordinate in these figures is the term "Δ mass fractions ln(dp)." In this variable, the mass fraction in size range is divided by Δ ln(dp). This latter term is literally the logarithm of the ratio of the upper to lower boundaries for each particle size channel. For each impactor stage, these lower and upper boundaries are the 50 % cut diameters of the stage and the 50% cut diameter of the preceding stage. In Figure 4, the size distributions measured at a tool speed of 3820 rpm appear to be smaller than the other size distributions measured by the MOUDI. This is consistent with the result of the statistical analysis. This result apparently explains the low probabilities for the tool speed related effects in Table 2. Figure 3 shows that machining conditions had little observable effect upon the size distribution measured by the APS. The results of the statistical analysis indicate that the mass fractions measured by the APS were largely unaffected by the independent variables; only tool speed ($p = 0.01$) affected the mass fraction collected in the size ranges. The tool speed effect uncovered by the statistical analysis is not evident in this plot.

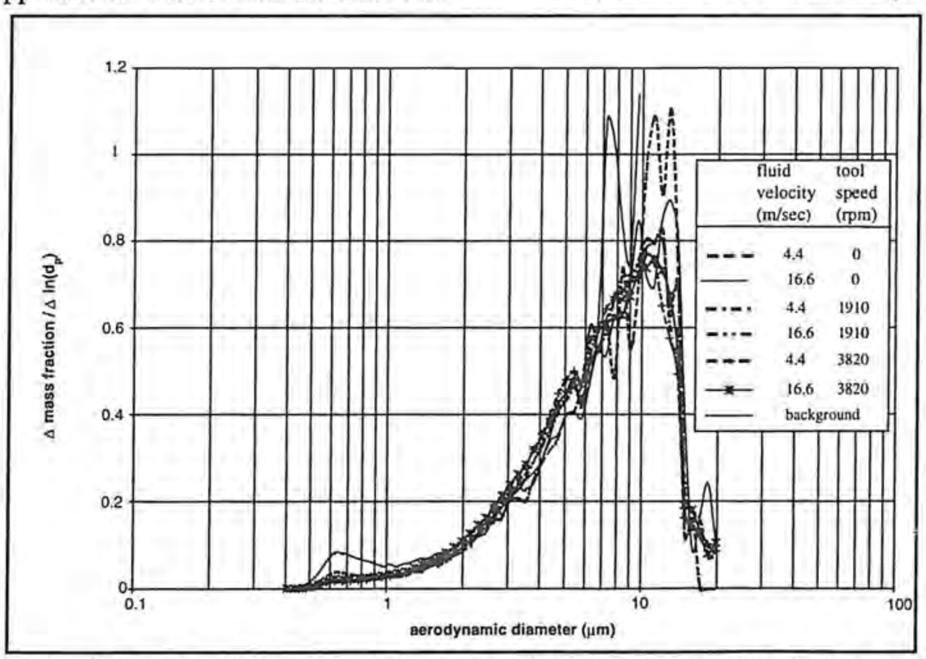


Figure 3. Test conditions have little observed effect upon size distributions by APS

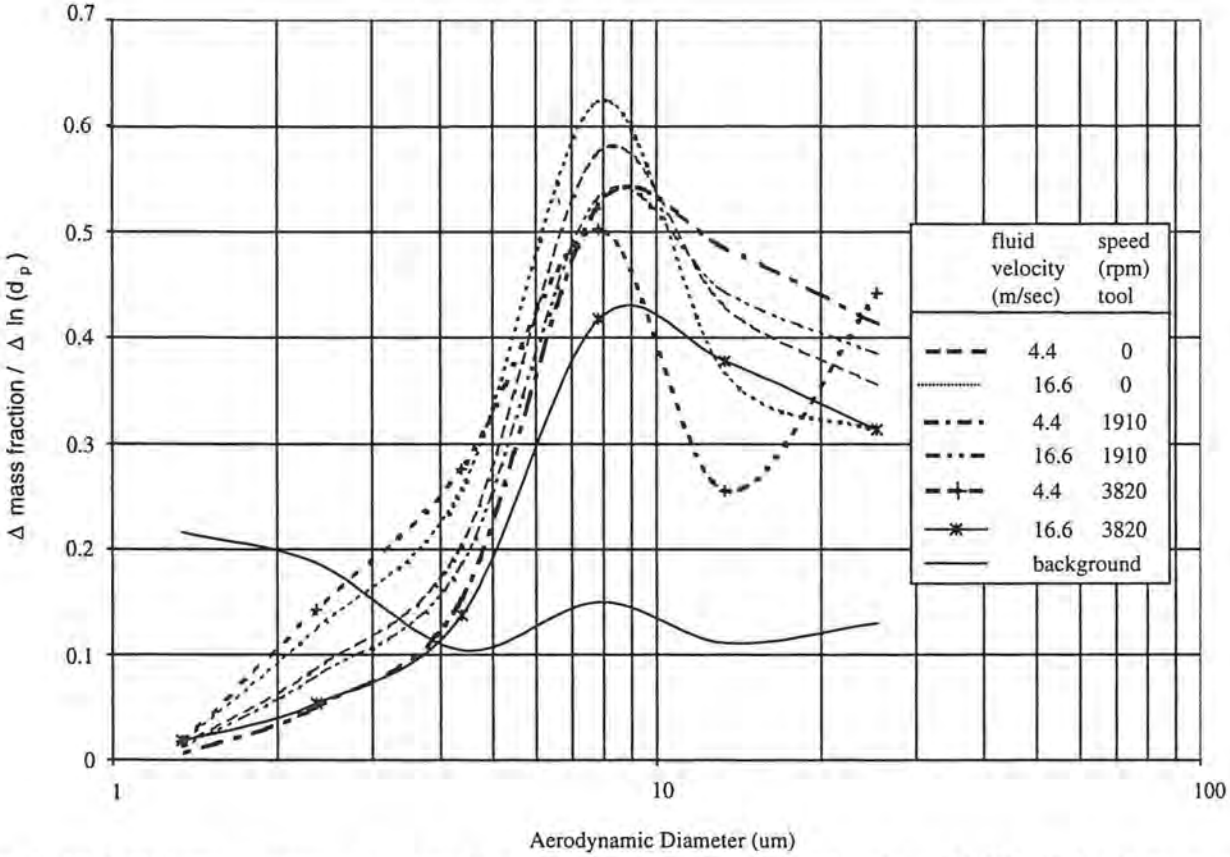


Figure 4. High tool speed appears to reduce the size of the aerosol measured by the MOUDI. This affect appears to be very pronounced in the 9-18 μm range (MOUDI stage number 1).

Mass Concentration Effects

The SAS General Linear Models Procedure was used to evaluate whether total aerosol concentration measured by the MOUDI and APS was affected by fluid velocity, tool rpm, metal cutting conditions, and the combinations of these variables.[7] Before data analysis, the logarithms of the concentrations were taken. Because the variances appeared to be non-homogenous, the analysis was weighted by the reciprocal of the variance for each combination of tool rpm and fluid velocity. Cutting condition was not considered in weighting the analysis, because variables involving cutting conditions did not affect the measured concentration. Table 2 presents the results of the analysis when the "cutting" was excluded from the analysis. When cutting was included in the analysis, its effect was insignificant ($p > 0.4$). Regardless of which analysis is used, fluid application velocity, tool speed, and the interaction of these two independent variables significantly affected the concentrations measured by the APS and the MOUDI ($p < 0.005$).

In Figures 5 and 6, mist generation is plotted as a function of tool rpm and fluid velocity. In both figures, mist concentration increases with increasing tool rpm and fluid application velocity. For the APS data presented in Figure 6, the effect of fluid velocity decreases with increasing tool speed. At low tool speeds, the higher fluid velocity is associated with higher concentrations. At the high tool speed, this difference appears to be very small. For the MOUDI data presented in Figure 5, fluid application velocity increased mist concentration at the 0 RPM tool speed. At the highest tool speed, the reverse occurred. The reason for this is unclear.

Temperature Measurements

During practically all experimental runs, the dew point and the ambient temperature in the duct were within 1-2° C of each other. The dew point was usually near the ambient duct temperature. Water was observed to leak from the duct. Apparently, the air in the duct was saturated under most conditions studied.

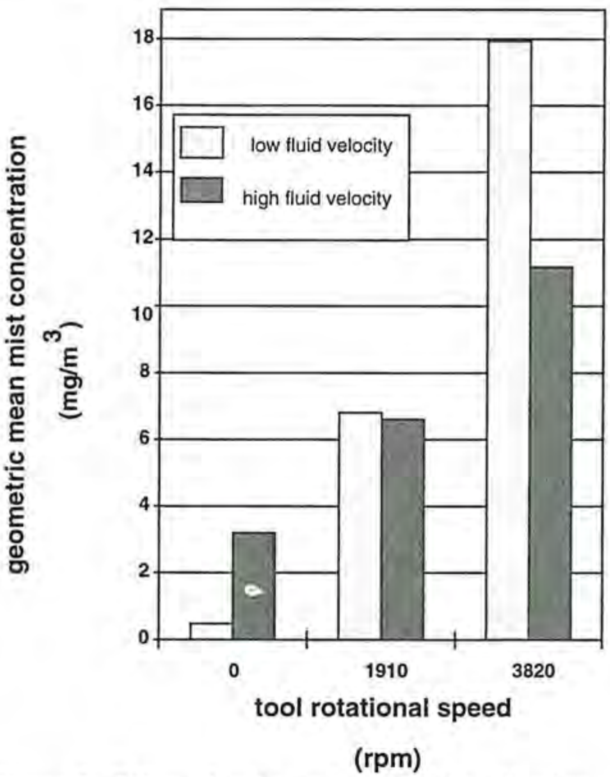


Figure 5. Effect of tool speed and fluid application velocity upon mist concentrations measured by the MOUDI

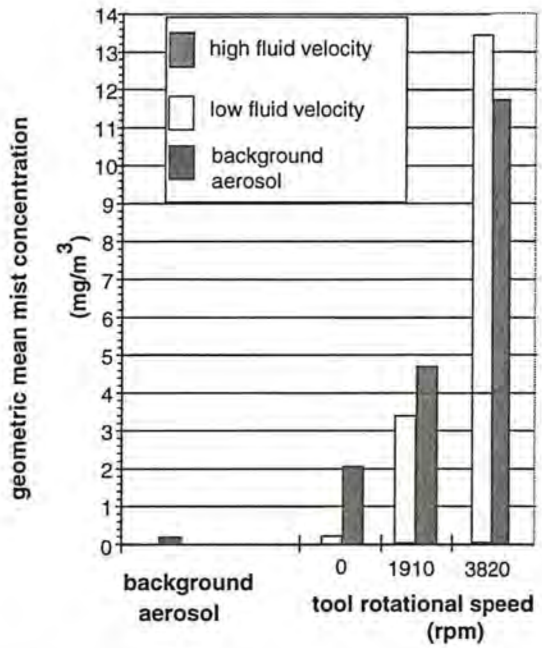


Figure 6. Effect of tool speed and fluid application velocity upon mist concentrations measured by the APS

CONCLUSIONS

The machining operations studied did not affect the size distribution of the aerosol. Furthermore, the aerosol size appears to have a mode of about 10 µm. Because of sampling line losses, the actual mode could be larger than 10 µm. Based upon the particle size results, air cleaners that are very efficient for particles larger than 1-2 µm will control practically all of the worker's exposure to metal removal fluids under the conditions studied here.

Figures 5 and 6 indicate a large difference in mist concentration at zero tool (rotational) speed. This suggests that a threshold effect is associated with mist generation. Increasing the fluid velocity by a factor of 3.8 increased the fluid kinetic energy by a factor of 14 and increased the mist generation by an order of magnitude. The geometric mean mist concentration at 1910 rpm and a fluid velocity of 4.4 m/sec was 0.2 mg/m^3 versus a geometric mean background mist concentration of 0.1 mg/m^3. If fluid velocities and the resulting mist generation are sufficiently minimized, perhaps mist exposures do not need to be controlled.

Threshold effects associated with mist generation need further investigation. Perhaps threshold criteria could be used to evaluate whether mist controls are needed before the production process is completely designed and installed in a plant. Conducting such research will involve manipulation of the metal removal fluid's rheological properties and it may involve a much more fundamental approach to the study of mist generation.

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The reader will notice a variety of nomenclature differences among authors when referring to these fluids which were the subject of the Symposium and of this volume. Indeed, even the Symposium title reflected some of this variation: "*Metalworking* Fluids Symposium II," and "The Industrial Metalworking Environment: Assessment and Control of *Metal Removal* Fluids." Lest we add to the confusion, our use of the term *metalworking* in the title "Metalworking Fluids Symposium II" was a conscious decision based on nothing more than to maintain continuity with the title from the first Symposium. It was for that reason that "Assessment and Control of Metal Removal Fluids" was added in recognition of, and to call attention to the fact that the vast majority of research and data to date has been generated on a subset or class of metalworking fluids known as **metal removal fluids**. In addition to metal removal fluids, the very general term 'metalworking' fluids also encompasses the large and general classes of *metal protecting* fluids, *metal forming* fluids, and *metal treating* fluids. Besides functional differences between metalworking fluid classes, there are substantial compositional differences both between and within classes. So while it is somewhat sloppy though quite common and generally harmless to use generic terms such as metalworking fluids, or machining fluids, or coolants, the reader should be well aware of these important distinctions and that in virtually all instances where there is a connection with purported health effects, the person is really referring to that subclass of metalworking fluids known as *metal removal fluids*.

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