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Mist Generation from Metalworking Fluids Formulated Using Vegetable Oils

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Metalworking fluid emulsion formulations produced from vegetable oils may be less toxic and may reduce disposal costs when compared with fluids formulated with petroleum-based oils. Experiments were performed on experimental emulsions made with unmodified and modified soybean oils to measure rates of mist production by impaction, centrifugal force and evaporation/recondensation mechanisms. Results were compared with measurements made using a commercial metalworking fluid emulsion formulated using vegetable oil and another made from mineral oil. The results indicated that most of the experimental fluids produced about the same amount of mist as the commercial fluids by impaction and more mist than the petroleum-based fluid by centrifugal force. However, an air-oxidized modified soy oil produced less mist by impaction than the petroleum-based fluid and about the same by centrifugal force. The experimental fluids produced between 30 and 90% less mist than the commercial fluids by evaporation/recondensation. The air-oxidized soybean oil was the most promising candidate among the experimental fluids for further testing in more realistic machining conditions.

Keywords: centrifugal force; evaporation; impaction; metalworking fluids; mist; vegetable oils

INTRODUCTION

Metalworking fluids (MWFs) are utilized during machining to cool, clean, lubricate and protect tools and workpieces. Several kinds of fluids have traditionally been used. Straight oils are highly refined petroleum-based oils with additives. Soluble oils are sold as concentrates of petroleum-based oils with emulsifiers and other additives that are mixed with water before use to form an emulsion. Synthetic fluids are concentrates of aqueous solutions containing no oil that are diluted further with water by the user. Semi-synthetic fluids are emulsions of oil in water with other dissolved chemicals that are further diluted with water before use. Most MWFs cycle through a delivery and return system for months or years before being replaced. During this period, the fluids often become contaminated with dirt, metal particles, microorganisms and tramp oils.

During high-speed machining, MWFs are usually applied in excess as a jet or spray. Thornburg and Leith (2000a) identified three mechanisms by which applied fluid can form an airborne mist: impaction, centrifugal force and evaporation/recondensation. Impaction occurs as MWFs, delivered at high velocities, break apart upon striking the surface of a tool or workpiece. The rotational motion of the tool or workpiece can eject liquid droplets from its wet surface through centrifugal force. Fluid reaching the hot cutting interface can evaporate as it absorbs heat from the process and then quickly recondense as it reaches cooler air surrounding the process. The droplets formed by these processes are of sizes that can travel throughout a workplace and be inhaled effectively by workers. Marano and Richert (1990) found that most MWF droplets formed primarily from straight and soluble oils were smaller than 4 μm in diameter. Woskie *et al*. (1994) measured soluble oil mist size distributions with mass median diameters ranging from 4.2 to 8.2 μm and geometric standard deviations between 2.2 and 3.7. More recently, Piacitelli *et al*. (2001) measured mass median diameters for soluble oil mist to be between 3.7 and 7.5 μm. In machining operations performed with

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soluble oils, Piacitelli *et al*. measured 242 total aerosol mass concentrations ranging from 0.07 to 2.41 mg/m^3 with a geometric mean of 0.34 mg/m^3 and a geometric standard deviation of 2.08. Simpson *et al*. (2003) took 296 total inhalable particulate measurements where water-mixed MWFs were used. Concentrations varied from <0.04 to 23.06 mg/m^3 with a geometric mean of 0.33 mg/m^3 and a geometric standard deviation of 3.05.

The National Institute for Occupational Safety and Health (NIOSH) estimated that about 1.2 million workers in the United States were exposed to MWF mist (NIOSH, 1977). Exposure to these droplets has been associated with a variety of respiratory problems including chronic cough and phlegm (Sprince *et al*., 1997), decreased lung function (Kennedy *et al*., 1989), occupational asthma (Rosenman *et al*., 1995), bronchitis (Zacharisen *et al*., 1998) and hypersensitivity pneumonitis (Shelton *et al*., 1999). NIOSH (1998) summarized a large number of studies that suggested an association between MWF mist exposure and cancer including cancers of the larynx, rectum, pancreas, skin, scrotum and bladder. Exposure to MWF mist may also cause skin disorders including irritation, rashes, oil acne, dermatitis, folliculitis and keratosis (Sprince *et al*., 1996; NIOSH, 1998).

In addition to being a potential human health problem, MWFs are also a concern for the ambient environment. Many US states and municipalities have classified used-MWFs as hazardous waste. The US Environmental Protection Agency has proposed a rule to impose technology-based effluent limitation guidelines and pretreatment standards on metal products and machinery production facilities, including metalworking facilities (EPA, 2001). Disposal of spent fluids involves separation of water from the rest of the MWF using evaporation, chemical treatment, membrane separation, biological treatment or some combination of these methods (ORC, 1999). The remaining fluid is then hauled away for incineration or recycling. Costs of fluid handling can comprise more than 15% of total machining costs in a well-run facility (DeVries and Murray, 1994).

As an alternative to petroleum-based MWFs, emulsions of modified vegetable oils in water could be utilized as MWFs. Vegetable oils are used industrially as carriers for herbicides (Kapusta, 1985), in coatings (Fulmer, 1985), as dust suppressants (Sonntag, 1985), and as plasticizer-stabilizers for polyvinyl chloride resins (Carlson and Chang, 1985). In addition, vegetable oils have long been used as lubricants (Nachtman and Kalpakjian, 1985). Limited quantities of MWFs formulated from vegetable oils are sold to machining operations. However, the capabilities of these formulations have not been extensively tested (Balulescu and Herdan, 1997).

Soybean oils are an appropriate choice as the base feedstock for MWF formulations because of their high degree of unsaturation, which provides opportunities for chemical modifications resulting in a wide range of products. These modifications before use as an MWF may provide the soybean oil with the improved oxidative stability necessary for functional MWFs. The possible reactions may involve either the carboxylic group or the carbon–carbon double bond in the unsaturated fatty acid. Reactions such as hydrogenation, epoxidation, co-sulfurization and oxidation may occur at a double bond, leading to a partial or complete cleavage of the bond.

Vegetable oil-based MWFs may pose fewer health concerns than traditional MWFs. When vegetable oils and mineral oils were injected directly into the lungs of test animals, the oils were removed slowly by bodily processes over several months (Pinkerton, 1928). Vegetable oils were removed mostly by expectoration and caused no long-term damage to the lungs. However, mineral oils were enveloped by phagocytic cells in the alveoli and slight fibroses were evident in the lungs after 2–3 months. When deposition and retention of vegetable, animal and mineral oil mists in the lungs of mice were compared, Shoskes *et al*. (1950) found that vegetable and animal oils were removed from the lung within 4 days whereas the petroleum-based oils were largely retained. After exposure to elevated mist concentrations for several weeks, mice exposed to mineral oil mists exhibited localized foreign body reactions of moderate severity in the lungs. Mice subjects exposed to vegetable oil mists showed almost no reactions. Although some studies have indicated that olive oil used to treat dermatological conditions can enhance contact dermatitis by both irritant and allergic mechanisms (Padoan *et al*., 1990; Kränke *et al*., 1997), vegetable oils themselves are not likely to present significant hazards to skin. In fact, vegetable oils are used frequently in dermal moisturizers and creams. Dermatological injury would be more likely to be caused by additives to vegetable oil emulsions, such as emulsifiers and biocides, than by the oil itself.

At the end of their useful lives, vegetable oil-based MWF emulsions are likely to be preferable to traditional petroleum-based MWFs because vegetable oils biodegrade more easily (Balulescu and Herdan, 1997; Goyan *et al*., 1998; Honary and Boeckenstedt, 1998). This improved biodegradability may lead to lower disposal costs. However, vegetable oil-based MWF formulations may also be more susceptible to unwanted microbiological growth as they are used. Increased microbiological contamination in any MWF is a concern because some microorganisms and their endotoxins may contribute to respiratory problems experienced by those working with the fluids (NIOSH, 1998).

Generation of MWF mist droplets by the evaporation/recondensation mechanism depends on the volatility of the compounds that make up the fluid. For both vegetable oil-based and petroleum-based emulsions, the water portion will evaporate readily when exposed to the heat of cutting and will probably remain in a vapor state because of the relatively high vapor pressure of water in air. However, the oil phase may recondense to form mist because the compounds in the oil have relatively low vapor pressure. Most mineral oils are composed of compounds having vapor pressures ranging from 10^{-2} to 10^{-10} mmHg (Volckens *et al*., 2000). However, vegetable oils are composed typically of compounds that are even less volatile. Therefore, vegetable oils are less likely to evaporate when exposed to the heat of cutting and are likely to produce less mist by the evaporation/recondensation mechanism than petroleum-based oils. Mist droplets from vegetable oil-based MWF formulations, generated by the impaction and centrifugal force mechanisms, are likely to be similar to traditional MWFs if the viscosity and surface tension of the formulations are similar.

The objective of this research was to measure mist generation by the impaction, centrifugal force and evaporation/recondensation mechanisms for several experimental vegetable oil-based MWF formulations. The amount of mist formation was compared with generation from a traditional petroleum-based soluble oil to determine whether vegetable oil emulsions offer the chance to lower MWF mist concentrations in workplaces.

EXPERIMENTAL METHODS

General approach

An apparatus was constructed and inserted into a wind tunnel to simulate mist formation from applied MWF emulsions by the impaction, centrifugal force or evaporation/recondensation mechanisms. The mist generated by this apparatus traveled through the wind tunnel and was sampled by a real-time particle counting and sizing instrument. Several experimental vegetable oil-in-water emulsions were tested in this apparatus as well as a commercial vegetable oil-based metalworking fluid emulsion and a commercial petroleum-based metalworking fluid emulsion. Real machining was not performed in this study because only small quantities of the experimental fluids were produced. More realistic tests would have required more fluid for adequate machining, and the fluids would have become contaminated rapidly, limiting the opportunity for replicate tests.

Oils

Five experimental emulsions were formulated and tested alongside one commercial petroleum-based formulation and one commercial vegetable oil-based formulation. Table 1 provides a summary of the fluids. The tribological characteristics of these oils were reported by John *et al*. (2004).

For the experimental emulsion concentrates, the base oil was plain or modified soybean oil. The Volga Oil Processing Company (Volga, SD, USA) supplied the plain soybean oil. Sulfur-modified and ozone-modified soybean oils were prepared from the plain oil. Air-oxidized soybean oil samples were obtained from the Urethane Soy Systems Company (Princeton, IL, USA). The number and mass average molecular weights and the viscosities of the experimental formulations are presented in Table 2 (John *et al*., 2004). The molecular weights of the experimental fluids are considerably higher than those expected in the commercial petroleum-based and vegetable oil-based formulations.

Raw soybean oil was modified by adding either sulfur or oxygen at the carbon–carbon double bonds. These reactions make the double bonds unavailable to other, less controlled and less desirable reactions during later use. Sulfur was selected because it is active at the temperature of the cutting edge of a tool and forms strong, wear-preventing bonds with metal. Oils oxidized either with air or ozone were expected to act similarly to sulfur-modified oil.

To produce a stable emulsion after the oil was mixed with water, a surfactant was used as an emulsifier. For the test oils, stable 5% oil-in-water emulsions were formed when the oil phase contained

Table 1. General description of test oils

Formulation designation	Composition
PCOM	Commercial petroleum-based soluble oil metalworking fluid concentrate
VCOM	Commercial vegetable oil-based metalworking fluid concentrate
SOY06	Soybean oil + 6% Eccoterge 200
SOY12	Soybean oil + 12% Eccoterge 200
SULF	Sulfur-treated soybean oil + 12% Eccoterge 200
OZ	Ozone-treated soybean oil + 12% Nikkol
AIR	Modified air-oxidized soybean oil + 12% Nikkol

Table 2. Molecular weight and viscosity of experimental MWF formulations

Formulation designation	Number average molecular weight	Mass average molecular weight	Concentrate viscosity (Pa-s)
SOY06 and SOY12	1360	1400	0.0628
SULF	2070	2550	0.203
OZ	2030	3400	0.158
AIR	3560	19 700	5.91

12% of either Eccoterge 200 (Eastern Color and Chemical Co., Providence, RI, USA) or Nikkol (Aldrich Chemical Co., Milwaukee, WI, USA) as an emulsifier.

An emulsion was formed by first mixing a concentrate with a small amount of water using an electric stirrer and then adding sufficient water to form a 5% concentrate-in-water emulsion. The concentration of the petroleum-based MWF was monitored using a handheld Brix refractometer (Westover Scientific, Woodinville, WA, USA). After each test, the concentration was recorded and, if required, corrected by adding water. The vegetable oil-based MWFs were monitored for water evaporation and corrected by maintaining the initial amount of each emulsion.

Test system

A test apparatus was constructed to simulate the impaction, centrifugal force and evaporation/condensation mechanisms that generate mist droplets during machining. The apparatus attempted to model the performance of a lathe. As shown in Fig. 1, a 3 inch diameter aluminum cylinder was driven by a lubricated air motor (Gast Manufacturing Inc., Benton Harbor, MI, USA). The rotational speed of the cylinder was controlled by adjusting the air pressure supplied to the air motor. MWF was applied and circulated using a commercial machine tool coolant kit (Little Giant, Oklahoma City, OK, USA). The fluid was applied near the top of the cylinder and drained through the bottom of the apparatus.

The test apparatus was installed as a section in a wind tunnel equipped with a variable speed fan (see Fig. 2). The cross-sectional area of the wind tunnel was 30.5 × 30.5 cm^2 (1.0 ft^2). The flow rate of air through the wind tunnel was maintained at 255 m^3/h by monitoring the velocity on the centerline of the tunnel using a calibrated VelociCheck thermal anemometer (TSI, St Paul, MN, USA). No humidity control was applied to the wind tunnel; the relative humidity of the building was generally well controlled to 45% ± 15%.

Generated oil mist was sampled at a location 130 cm downstream from the center of the cylinder. The sampling probe was located at the center of the tunnel and oriented into the incoming flow. Air traveled into the probe, which had a diameter of 6.3 mm, and then made a 90° turn to pass through the bottom of the wind tunnel. The air was drawn through the probe into an Aerodynamic Particle Sizer (APS) 3310 (TSI). The APS counted and sized the MWF mist in real time for particles with aerodynamic diameters between ~0.5 and 30 μm. The APS collected samples integrated over 1 min increments.

Because the APS operated at an air flow rate of 5.0 l/min, the sampling into the probe was superisokinetic. Estimates (Brockmann, 2001) suggested that the aspiration efficiency was >81% for 15 μm aerodynamic diameter particles, >90% for 10 μm

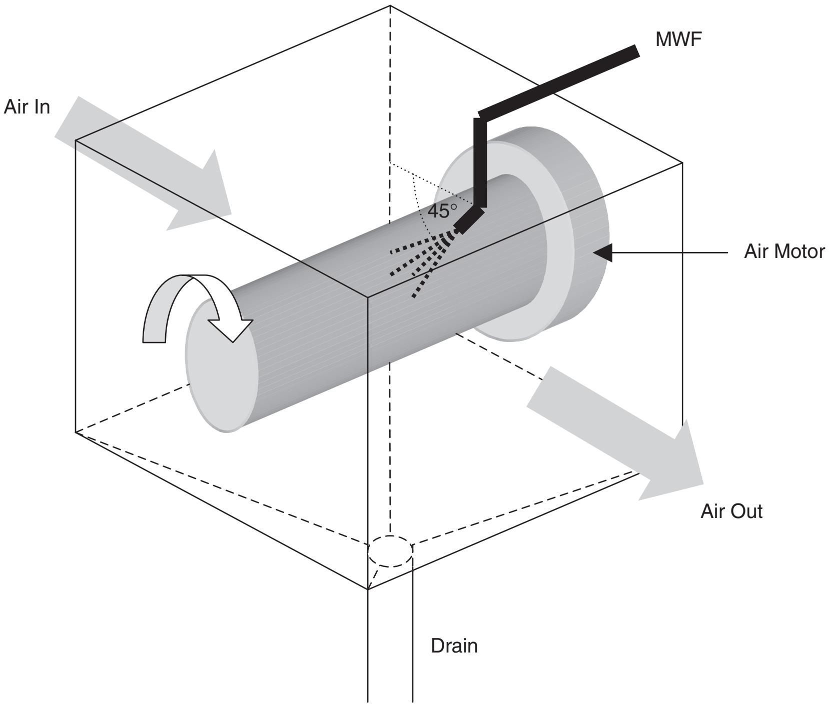

Fig. 1. Diagram of mist generation apparatus.

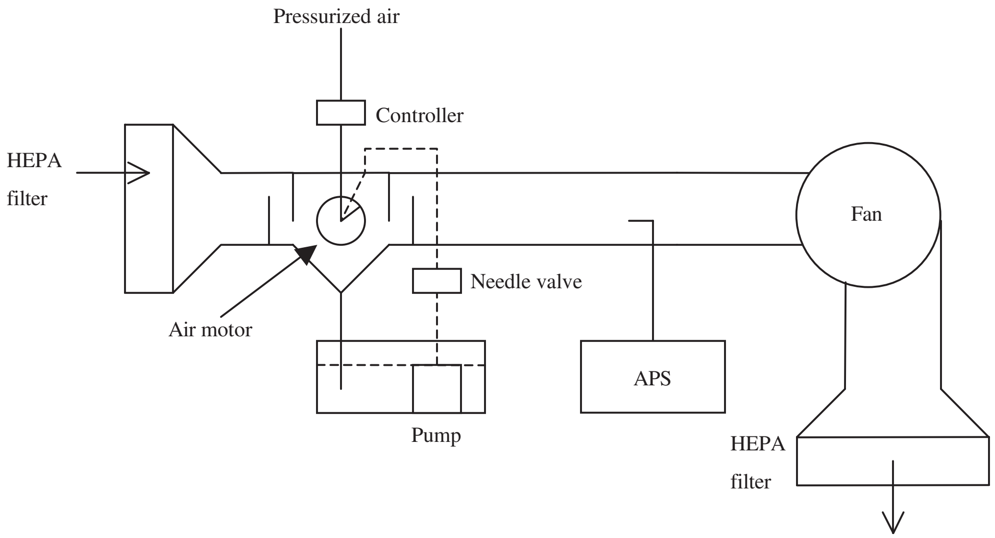

Fig. 2. Diagram of test apparatus installed in wind tunnel.

aerodynamic diameter particles and even higher for smaller particles. These relatively small errors were deemed acceptable for the purposes of comparing the experimental MWF formulations with the commercial products.

To test the effect of impaction on mist generation, MWF was applied to the center of the cylinder when it was stationary. The angle between the MWF flow and the horizontal was ~45° (see Fig. 1). The fluids were applied at a flow of 5.7 l/min. This flow was higher than the flows used by Thornburg and Leith (2000b) but lower than fluid flows utilized in many high-speed machining operations. The flow was controlled using a precision needle valve and monitored using a rotameter. For each experimental fluid and for the commercial vegetable oil-based MWF, the mist generation was measured in three separate tests on three different occasions. For the petroleum-based soluble oil, six separate tests were conducted. In each test, the APS collected five 1 min samples of the size distribution as the mist was generated. In addition, at least 10 measurements of the background particle concentration in the wind tunnel were made during each test.

For measurements of mist generation by centrifugal force, the aluminum cylinder was rotated using an air motor at an average speed of 2200 rpm. This rotational speed, similar to the highest rotational speed utilized by Thornburg and Leith (2000b), was measured using a photo tachometer (Extech Instruments, Waltham, MA, USA) after running the air motor at a targeted speed for 10 min. MWF was applied at a flow rate of 5.7 l/min. The experimental fluids and the commercial vegetable oil-based MWF were each tested three times, and the commercial soluble oil was tested six times. During each test, the APS collected five size distribution samples as mist was generated.

For testing evaporation/recondensation, a stainless steel cartridge heater was mounted at the location on the cylinder where the flow of MWF impacted. The current supplied to the heater was controlled using a Robtemp stepless heat control (George Ulanet Co., Newark, NJ, USA). During the evaporation/recondensation tests, the cylinder was not rotated. After waiting 10 min for the heater to reach a constant temperature of 210°C, MWF was applied at a flow rate of 1.9 l/min. The surface temperature of the heater was measured using an infrared thermometer (Raytek, Santa Cruz, CA, USA). A flow of 5.7 l/min was not selected for the evaporation/recondensation tests because the splashing of MWF was severe enough at this elevated flow to cause a shortage problem for the heater. For the experimental formulations and the commercial vegetable oil-based fluid, mist generation was measured on three occasions. Six tests were conducted on the petroleum-based MWF. In each test, the APS collected ten 1 min samples of the size distribution after the fluid was applied to the heater. However, the generation was not steady and declined over time. Thus, the most useful data for evaporation/recondensation droplet production were collected in the first 1 min sample for each test. In addition to collecting data with the heater on, mist levels were measured with the heater off to allow the effects of droplet formation by impaction to be separated from those of formation by evaporation/recondensation.

The temperature of the fluid in the sump was measured before, during and at the conclusion of each test. The differences between the starting and ending temperature for each run were calculated from the readings. The initial and final fluid temperatures and the temperature change were averaged for each kind of fluid for the impaction and centrifugal force tests, which were conducted together, and for the evaporation/recondensation tests.

Data analysis

Counts for particles larger than ~3 μm in aerodynamic diameter were subject to errors caused by 'phantom particles' created by sizing deficiencies inherent to the APS 3310. Heitbrink and Baron (1992) developed a procedure to correct for the influence of phantom particles by utilizing data from both the large and small particle signal processors in the APS. This method was employed to correct particle counts measured by the APS. Number concentrations were calculated from particle count measurements by dividing the counts by 1 l, the volume of unfiltered air drawn into the sensing region of the APS during each 1 min sample.

For the size distribution measurements from the impaction tests, each concentration measurement was corrected by subtracting the average of the background concentrations for particles of the same size in the same test. Then, the mean and standard deviation of particle concentrations from all measurements on each fluid were calculated for each aerodynamic diameter. Using these results, the expected values and standard errors of the ratio of particle concentrations generated when each vegetable oil-based fluid was used to the particle concentrations produced when the petroleum-based soluble oil was used were estimated using expressions provided by Mood *et al*. (1974).

In the centrifugal force tests, the measured size distributions were a combination of droplets generated by both the impaction and centrifugal force mechanisms. Thus, each concentration measurement in the centrifugal force tests was corrected by subtracting the average of the particle concentrations from the impaction test conducted at the same time. After the means and standard deviations of the corrected mist concentrations were computed for each fluid and droplet size, the expected values and standard errors of the mist concentrations for the vegetable oil formulations divided by the corresponding soluble oil mist concentrations were estimated according to Mood *et al*. (1974).

The size distributions measured during the evaporation/recondensation tests are similarly a combination of droplets generated by both impaction and evaporation/recondensation. Therefore, each concentration reading made with the heater at 210°C was corrected by subtracting the average of the concentration measurements made with the heater turned off. Means and standard deviations of corrected concentrations were calculated for each combination of fluid and aerodynamic diameter. Then, the expected values and standard errors of the ratios of the vegetable oil formulation concentrations to the soluble oil concentrations were estimated using the Mood *et al*. (1974) expressions.

RESULTS

Figure 3 presents the average size distributions measured for the petroleum-based soluble oil MWF for the impaction, centrifugal force and evaporation/recondensation mechanisms. The highest particle concentrations were observed for the evaporation/recondensation mechanism, followed by the centrifugal force mechanism and then the impaction mechanism.

The concentrations measured for droplets produced by the impaction mechanism for the six vegetable oil-based emulsions compared with the levels measured for the commercial soluble oil are presented in Fig. 4. Between aerodynamic diameters of 1 and 10 μm, the relative particle counts are grouped close to 1, meaning that the vegetable oil-based emulsions produced about the same quantity of particles by impaction as the petroleum-based emulsion, except for the air-oxidized experimental fluid, which produced fewer droplets. For droplets larger than ~10 μm, the soluble oil produced fewer droplets than the other fluids.

Relative number concentrations produced by the centrifugal force mechanism are shown in Fig. 5. Most of the vegetable oil-based fluids generated 3–7 times more droplets by centrifugal force than the soluble oil did. However, the numbers of droplets measured for the air-oxidized soybean oil were generally not statistically different from the quantity of mist observed using the soluble oil.

Figure 6 displays the relative concentrations produced by the evaporation/recondensation mechanism. Although the commercial vegetable oil-based emulsion demonstrated about the same amount of mist generation as the soluble oil, the experimental fluids generally exhibited between 30 and 90% less mist formation than the soluble oil.

For the impaction and centrifugal force tests, the initial fluid temperatures ranged from 23 to 27°C, and final temperatures ranged from 26 to 31°C. The temperature change during these tests varied from +2 to +7°C. For the evaporation/recondensation tests, the average starting temperatures were between 24 and 29°C, and the temperatures at the end were between 33 and 36°C. The temperature change ranged from +7 to +11°C.

DISCUSSION

Although the experimental methods used in this study simulate the mist formation mechanisms identified by Thornburg and Leith (2000a), they are

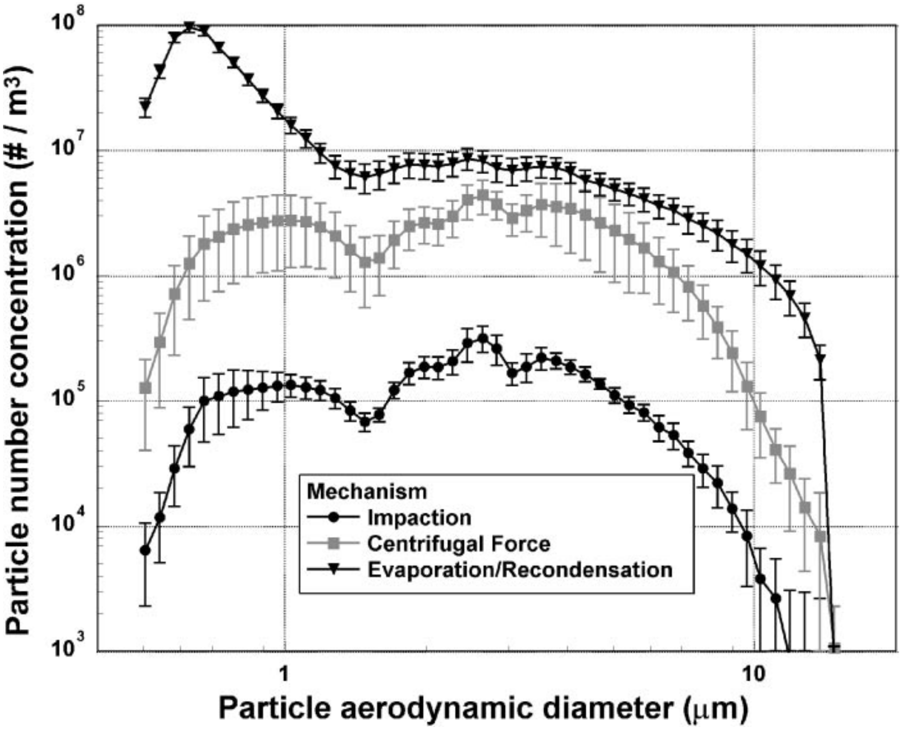

Fig. 3. Aerodynamic size distributions of mist produced using petroleum-based soluble oil by the impaction, centrifugal force and evaporation/recondensation mechanism tests. Error bars represent one standard error for the particle concentrations.

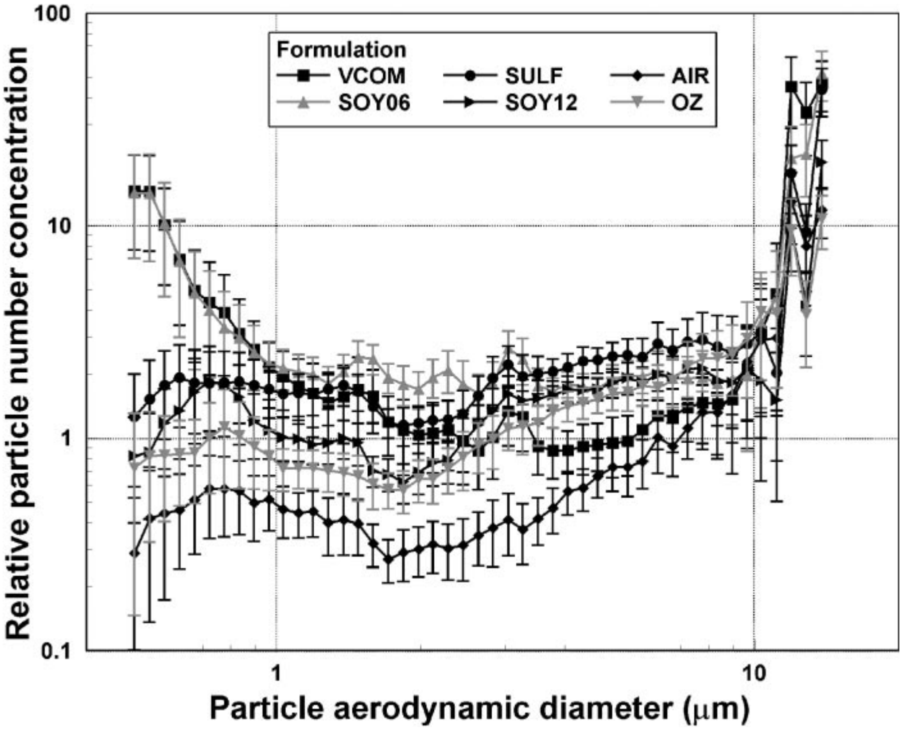

Fig. 4. Particle concentrations produced using the commercial vegetable oil-based fluid and the five experimental fluids relative to concentrations produced using the petroleum-based soluble oil in the impaction tests. Error bars represent one standard error around the expected value.

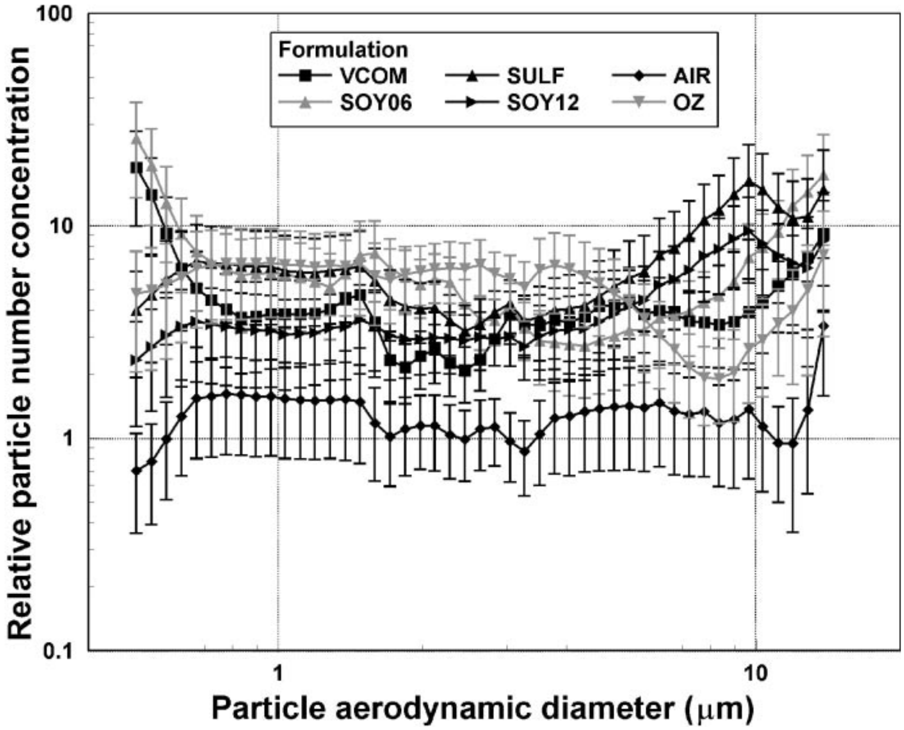

Fig. 5. Particle concentrations produced using the commercial vegetable oil-based fluid and the five experimental fluids relative to concentrations produced using the petroleum-based soluble oil in the centrifugal force tests. Error bars represent one standard error around the expected value.

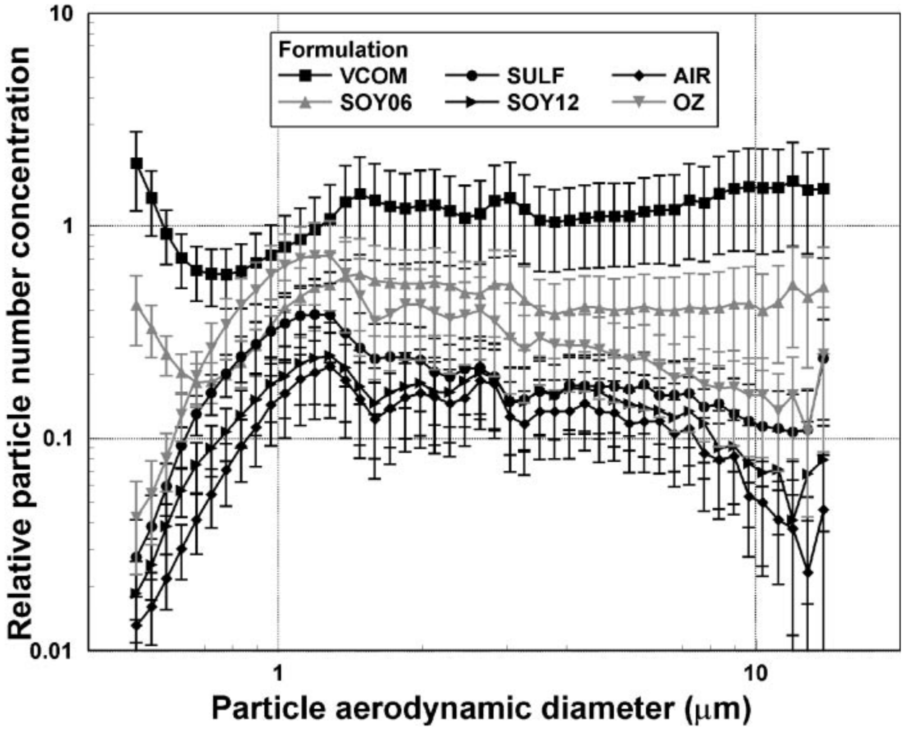

Fig. 6. Particle concentrations produced using the commercial vegetable oil-based fluid and the five experimental fluids relative to concentrations produced using the petroleum-based soluble oil in the evaporation/recondensation tests. Error bars represent one standard error around the expected value.

imperfect. In particular, the evaporation/recondensation simulation is not a steady process: the heater is raised to a set temperature, the fluid is applied and then the generated mist is sampled. The method simulates a quenching process more closely than a continuous machining operation. In addition, the impaction and centrifugal force mechanisms are most appropriate for simulating a lathe operation. Other machining processes may produce mist of different sizes or generate droplets by the various mechanisms in different proportions than those found in this study.

Despite these concerns, the size distributions shown in Fig. 3 agree well with the mist size distributions measured by Thornburg and Leith (2000a) for petroleum-based soluble oils using a lathe. For the evaporation/recondensation mechanism, Thornburg and Leith observed high levels of particles smaller than 1 μm in diameter, similar to the results shown in this study. However, they observed more particles 10 μm and larger formed by the centrifugal force mechanism than the tests in this study. Although the causes for the oscillations in the size distributions between 1 and 4 μm (Fig. 3) are not known, the fluctuations are probably artifacts related to processes within the APS 3310 or treatment of data by the APS software because they appear for all three mechanisms.

The evaporation/recondensation test results presented in Fig. 6 indicate that the experimental fluids generated substantially less mist than the commercial petroleum-based and vegetable oil-based MWF emulsions. Because this mechanism produces the most mist collected during sampling of the respirable and thoracic size fractions (Thornburg and Leith, 2000b), the lower mist generation suggests that the experimental fluids might provide an opportunity to reduce respirable and thoracic mist concentrations if they were able to be used in machining facilities. This reduction in mist formation by evaporation and recondensation probably occurs because the compounds comprising the multicomponent experimental formulations are less volatile than the commercial products. As part of this study, an attempt was made to analyze the test fluids using a gas chromatograph (GC) with a flame ionization detector. Although the commercial products eluted readily from the GC column, relatively little of the experimental fluids could be driven through the column. The molecular weights shown in Table 2 also suggest that the compounds in the experimental formulations should have exhibited minimal evaporation because compounds with such high molecular weights usually have extremely low vapor pressures.

The results of the impaction and centrifugal force mechanism tests in Figs 4 and 5 generally indicate that the petroleum-based emulsion generated less mist than the vegetable oil-based emulsions. The reason that the soluble oil has an advantage is not clear. However, one of the experimental fluids, the air-oxidized soybean oil, performed better than the soluble oil in the impaction test and almost as well as the soluble oil in the centrifugal force test. The reason that this fluid may have performed better than the other experimental formulations could be that the oil phase is much more viscous, as shown in Table 2. Although Thornburg and Leith (2000a) found that small differences in viscosity did not influence mist generation, the substantial difference in viscosity for the air-oxidized soybean oil may have had a much more important effect. This finding suggests that emulsions made from more viscous fluids may offer benefits for reducing mist generation in machining operations.

The ozone-treated oil performed better than the soluble oil in the impaction tests for droplets between 0.2 and 3 μm in diameter. However, for larger droplets in the impaction and centrifugal force tests, the ozone-treated oil performed significantly worse than the petroleum-based fluid.

Corrections for background particle counts were important for the impaction tests for droplets smaller than ∼1 μm in aerodynamic diameter. Better sealing of the wind tunnel may have been able to reduce the significance of these background particles. Corrections for the APS phantom particles influenced results for particles larger than ∼10 μm in aerodynamic diameter.

In Fig. 4, far fewer droplets larger than 10 μm were counted for the petroleum-based soluble oil than for the vegetable oil formulations. The reason for these reduced counts is uncertain. However, the finding could be related to the relatively low levels of such large droplets present in the size distributions. In addition, the correction for the phantom particles counted by the APS may influence the results for the largest droplets. Size distributions with more particles, such as the experimental vegetable oil formulations in Fig. 4, tend to have disproportionately more phantom particles owing to a greater likelihood of coincidence in the APS (Heitbrink *et al.*, 1991).

Differences in the initial and final temperatures of the fluids and the temperature change of the fluids did not appear to influence results. Although both fluid viscosity and compound vapor pressure depend on temperature, viscosity does not vary widely over a relatively narrow temperature range and the vapor pressure of the evaporating fluids was probably influenced more by the temperature of the heating rod than by the fluid temperature before it reached the rod.

In general, results suggest that overall mist levels would decrease if a vegetable oil emulsion, particularly the air-oxidized oil, were used as an MWF in place of a soluble oil. The reduced mist generation by evaporation/recondensation for a vegetable oil emulsion would also lead to fewer small mist droplets.

A larger droplet size distribution would make distribution of mist throughout a workplace more difficult. Thus, workers would probably inhale less mist. In addition, decreased mist generation would reduce dermal exposure to droplets (Schneider *et al*., 2000).

The results in these tests do not indicate at all whether the experimental vegetable oil-based emulsion formulations would serve adequately as MWFs in real machining facilities. In addition to their cooling and cleaning properties, MWFs must lubricate the tool and workpiece adequately, provide an adequate surface finish, protect the cutting tool and last a long time. These capabilities have not yet been assessed for the experimental fluids. In particular, oxidative stability and resistance to microbiological degradation are a concern. Although the experimental emulsions were formulated with vegetable oils modified to improve both stability when heated and resistance to microorganisms, the ability of the experimental formulations to resist chemical modification and microbiological growth must be assessed. If the vegetable oils change chemically when heated they would probably not perform as intended. In addition, if the formulations allow for easy growth of bacteria and fungi, the fluid will not perform its functions properly, will cause unwanted odors and may contribute to adverse health effects among workers.

Ultimately, the best way to reduce exposure to MWF mists would be to reduce the use of MWFs. Tool and machine manufacturers are developing dry and near-dry machining systems that may penetrate the machining market significantly in the future (Canter, 2003). However, alternatives to the use of MWFs for most severe, high-speed processes are not anticipated any time soon.

CONCLUSIONS

Stable experimental oil-in-water emulsions made from modified and unmodified soybean oil were formulated for potential use as MWFs. When these formulations were subjected to tests intended to simulate mist formation by impaction, the experimental fluids performed similarly to a current petroleum-based soluble oil MWF. In tests of mist production by centrifugal force, the soluble oil generally formed less mist than the experimental MWFs. However, the air-oxidized modified soybean oil performed much the same as the soluble oil. In tests of mist formation by the evaporation/recondensation mechanism, the experimental fluids generated much less mist than the soluble oil. These findings suggest that use of the experimental formulations could possibly lead to reduced worker exposures to the respirable and thoracic fractions of MWF mist generated by evaporation and recondensation. Moreover, these results indicate that emulsions formulated with low-volatility, high-viscosity vegetable oils are likely to lead to less mist formation than emulsions formulated from more volatile, less viscous fluids.

The experimental fluid that performed best in these experiments was the air-oxidized modified soybean oil formulated with 12% Nikkol emulsifier. Actual machining tests with this fluid are necessary to verify reductions in mist generation and to determine whether the formulation can serve adequately as a MWF under more realistic conditions.

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