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Performance of Industrial Mist Collectors Over Time

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Effective, economical control of metalworking fluid mists at the source is important, because exposure to these mists may cause adverse health effects. This study investigated performance changes over time for industrial collectors that removed metalworking fluid mist in the laboratory and in a transmission plant. Aerosizers were used to measure the efficiency of each stage in several multistage collectors as a function of mist droplet diameter, for up to one year of continuous operation. Metal-mesh, first-stage filters operated at low pressure drops and were effective at removing droplets larger than 3 to 5 θm in diameter. Some second-stage filters worked better than others. Both "65 percent" and "95 percent" cartridge filters failed after only a few weeks; their efficiencies decreased substantially over that time. Pocket filters and cylindrical cartridges used as second-stage filters also decreased in efficiency for submicron droplets. Whereas filters for solid particles load continuously to form a dust cake that increases efficiency, mist filters form no cake and load only to the point where collection equals drainage. As a mist filter loads, the interstitial gas velocity increases, so that efficiency decreases for small droplets that collect by diffusion. Although a third-stage 95 percent DOP filter showed important decreases in efficiency over time for submicron droplets, third-stage HEPA filters operated with efficiencies that consistently approached 100 percent for droplets of all sizes, even after one year of operation. These results suggest that the performance of second-stage filters can be improved if they can be made to drain collected liquid more effectively. For high efficiency, mist collectors should use a HEPA filter as a final stage.

Keywords Mist Collectors, Metalworking Fluids, Oil Mist

Metalworking fluids are used to cool and lubricate the cutting tool and stock used in machining and grinding processes and to remove chips generated by the cutting action. Mist is generated by the application of the fluid, by the interaction of the cutting tool, work piece, and fluid, and by evaporation and condensation processes associated with heat generated as machining takes place.(1,2) Four types of fluids are generally used in industry: straight oils, which are undiluted mineral and fatty oils; soluble oils, which are water emulsions of mineral and fatty oils; synthetic fluids, which contain no oils, but are chemical solutions of organic compounds and inorganic salts in water; and semi-synthetic fluids, which are emulsions of mineral oil with water and the chemicals found in synthetics. To improve their overall performance, these oils and fluids may be treated with additives such as biocides, surfactants, extreme pressure agents, anti-oxidants, and corrosion inhibitors.

Inhalation and dermal exposures to metalworking fluids, their additives, and the contaminants from the metal machining process have been associated with adverse health effects. Primary concern(3) focuses on cross-shift changes in respiratory function,(4) cancers of the respiratory tract and gastrointestinal tract,(5–7) asthma,(8) acute and chronic respiratory dysfunction,(9,10) dermatitis,(11) and allergic reactions.(12) Skin cancers(13,14) associated with metalworking fluids may have been due to fluid constituents no longer present. Adequate control is necessary as an estimated 1.2 million workers in the United States are exposed to metalworking fluids.(15)

Mist generated by machining processes can be captured, then ducted to a collector that removes the mist and recirculates cleaned air back to the plant. The most effective way to control exposure to metalworking fluid mist is to prevent mist from entering plant air. Although some firms have extensive experience at building mist control equipment, a test procedure for evaluating the performance of this equipment against metalworking fluids did not exist until recently;(16, 17) hence, effective technology for a given application was often difficult to identify.

Our initial research on metalworking fluids focused on the development of a laboratory protocol to evaluate mist collector performance, and the application of this protocol to assess the performance of nine commercially available collectors.(17) In those laboratory tests, substantial differences in efficiency and pressure drop were found among the collectors and their components. Based on these studies several promising technologies were identified, each of which was then evaluated in long-term tests both in the laboratory and at a truck transmission plant.

Table I outlines the three long-term studies. Each collector was sized to process 0.47 m^3/s (1000 cfm) of air. In Study #1, the efficiencies of two identical collectors were evaluated when challenged with hobbing oil mist (Metkut F3C2BA, Metalworking Lubricants Co., Birmingham, MI), a straight oil; one collector was tested in the laboratory and the other on a gear-cutting operation at the transmission plant. These collectors contained three filters arranged vertically in series: a first-stage four-inch metal mesh filter, a second-stage pocket filter, and a third-stage 95 percent DOP filter. Identical first- and second-stage filters were used in the two collectors; the sizes of the third stages were slightly different to accommodate different size bays. In each study, performance evaluations continued until the filter components failed or one year elapsed.

Study #2 was conducted to evaluate collector performance at removing mist of soluble oil (Kleenkut 6222, DA Stuart Co., Warrenville, IL), the most prevalent metalworking fluid in the automobile industry. Soluble oil was used in a concentration of 10 percent oil in water by volume. The same two collectors used in the first study were tested, one in the laboratory and one at the transmission plant on a gear-grinding operation. The filters tested were identical to those in the first study with the exception that a HEPA filter replaced the 95 percent DOP third-stage filter.

Although the final filter designated as "95 percent DOP" in the work presented here might be called a HEPA filter in the trade, an important distinction exists between this filter and a true HEPA. In the present context, a 95 percent DOP filter carries a manufacturer's specification of 95 percent efficiency as measured using a cold DOP test, whereas a true HEPA filter carries a manufacturer's specification of 99.97 percent efficiency with the same test. The filters are similar in size, but the HEPA filter contains more filtration media as shown in Table I.

Study #3 was conducted at a valve body line in the transmission plant where semi-synthetic fluid was used. First, using the same collector as in studies #1 and #2, a test was conducted to evaluate this collector's performance at removing mist of semi-

TABLE I
Study designs and component characteristics in the collectors evaluated

Study	Components characteristics	Study sites	Duration
Study #1: Hobbing Oil	Metal mesh, 50.2 cm × 50.2 cm × 9.2 cm ribbon-fibers 1.14 mm × 0.08 mm 10-pocket filter, 67.3 cm × 90.2 cm, $A = 12.1\ m^2$ glass fibers 3.2 μm diameter 95% DOP filter, 61 cm × 61 cm × 29.8 cm $A = 18.2\ m^2$ (lab) 59.4 cm × 59.4 cm × 29.2 cm $A = 21.3\ m^2$ (plant)	Lab and plant	1 year each
Study #2: Soluble Oil	Metal mesh, same as Study #1 10-pocket filter, same as Study #1 HEPA filter, 61 cm × 61 cm × 29.8 cm $A = 29.1\ m^2$ (lab) 59.4 cm × 59.4 cm × 29.2 cm $A = 25.7\ m^2$ (plant)	Lab and plant	1 year each
Study #3a: Semi-Synthetic Fluid	Metal mesh, same as Study #1 10-pocket filter, same as Study #1 HEPA filter, same as Study #2 (plant)	Plant	5 months
Study #3b: Semi-Synthetic Fluid	Metal mesh, same as Study #1 "95%" cartridge filter, 61 cm× 61 cm × 30.5 cm HEPA filter, same as Study #2 (plant)	Lab and plant	1 day lab; 2 weeks plant
Study #3c: Semi-Synthetic Fluid	Metal mesh, same as Study #1 "65%" cartridge filter, 61 cm× 61 cm × 30.5 cm HEPA filter, same as Study #2 (plant)	Lab and plant	1 day lab; 5 weeks plant
Study #3d: Semi-Synthetic Fluid	Wire mesh filter, 59.7 cm × 59.7 cm × 4.8 cm formed wire screen; wire diameter 0.24 mm Cylindrical cartridge and wrap assembly 53 cm h × 55 cm dia; 6.35 cm pleats; $A = 18.3\ m^2$; average fiber diameter 11.2 μm HEPA filter, same as Study #2 (plant)	Plant	8 months

synthetic fluid, (Study 3a). In this application, filter components lasted five months. Next, two different cartridge filters were evaluated as replacements to the second-stage pocket filter in the collector (studies 3b and 3c). Finally, an eight-month test was conducted with a three-stage collector that employed a first-stage wire mesh filter, a second-stage cylindrical cartridge-wrap assembly, and a third-stage HEPA filter (Study 3d). The wire mesh filter consisted of alternating layers of straight and serpentine-shaped wire screens stacked vertically. The serpentine-shaped screens were reverse crimped along their medial axis so that ridges on one-half of the screen were followed by grooves on the other half. The second-stage assembly was composed of an inner pleated cartridge and an external three-layer wrap that attached to the top of the cylindrical cartridge by hook-and-loop fasteners. The third-stage was a HEPA filter.

The objectives of all three studies were: (1) to identify the relationship between removal efficiency and droplet diameter for each stage of the collectors as well as for the complete collector when challenged with the metalworking fluid mist, (2) to determine how the relationship between droplet collection efficiency and droplet diameter changed with time, and (3) where applicable, to confirm the laboratory findings with parallel tests conducted in the transmission plant.

METHODS

Laboratory Tests

For the laboratory portions of Study #1 and Study #2 (see Figure 1), the testing process was as described previously(17) with the following modifications. A six-jet nebulizer (BGI Inc., Waltham, MA) was used to introduce approximately 10 mg/m^3 mist alternately at points upstream (Position 2) and downstream (Position 1) from the collector. Droplets produced by the nebulizer were counted with an Aerosizer (TSI Particle Instruments Division, Amherst, MA) nine times, five times with the nebulizer at Position 2 and four with the nebulizer at Position 1. To ensure that any count differences observed between the positions were not caused by subtle shifts in the mist generation rate, the nebulizer was alternated between the positions in a 2-1-2-1-2-1-2-1-2 pattern, with the nebulizer in operation the entire time.

Weekly efficiency tests were run on the housing alone, housing and metal mesh filter, housing and pocket filter, housing and 95 percent DOP filter, and the housing with all three filters installed. Each week, prior to the start of these tests, all filters were removed and weighed; the amount of fluid that had entered and drained through the system was also determined. In addition, the temperature and relative humidity of the air entering the test system and the pressure drop across the collector and each individual component were measured. For those times when efficiency tests were not in progress, the collector was conditioned 24 hours per day with about 35 mg/m^3 of mist generated from a 40-jet nebulizer. These levels of mist, which are greater than would be found in most plant installations, were generated to accelerate changes in component performance.

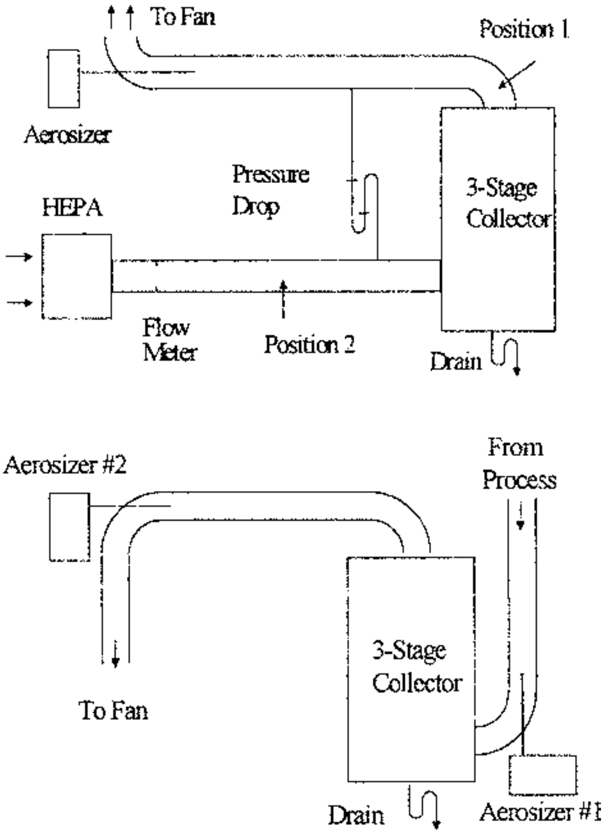

FIGURE 1
Schematic sketches of the test setup in the laboratory at the University of North Carolina (top) and at the transmission plant (bottom).

The count data measured and stored by the Aerosizer were analyzed. From this information, efficiency measurements as a function of droplet diameter and operating time were calculated for each component of the collector and for the complete collector with all filters installed.

Plant Tests

In Study #1 tests at the plant, mist was generated from two completely enclosed hobbing machines located 11 m upstream of the collector. The hobbing process involved the shearing of nearly 40 g of steel every 30 seconds amidst a constant flow of hobbing oil. For Study #2 plant tests, mist was generated from the steady application of approximately 10 percent soluble oil onto a grinder. The machine was serviced by a canopy-type hood from which ductwork extended approximately 14 m to the collector. When this grinder required extensive repairs after eight months, the canopy hood was moved to a new grinder that was totally enclosed and operated at a higher production rate. For Study #3 tests, mist was generated by the application of semi-synthetic fluid onto many drilling operations on an aluminum valve body line located about 14 m upstream of the collector.

Mist captured by several canopy-type hoods was drawn through a 46-cm-diameter duct to the large collector that normally controlled mist from this process. Branching from this main duct was a 20-cm-diameter duct that carried mist 8 m to the test collector.

Monthly tests were conducted in the same manner at each site in the plant to measure collector and component efficiency, component weight, and the pressure drop of each component at rated flow. Efficiency measurements were made for the housing alone, the housing plus the first stage, the housing plus first and second stages, and the housing with all three stages installed. The concentration and size distribution of mist upstream and downstream of the collector were measured simultaneously, 10 times, using two Aerosizers. To eliminate any measurement bias due to differences between the Aerosizers, the instruments were then interchanged and another complete set of measurements was made. The count data measured and stored by the Aerosizers were analyzed. From this information, penetration measurements were calculated for each component of the collector and for the complete collector with all filters installed.

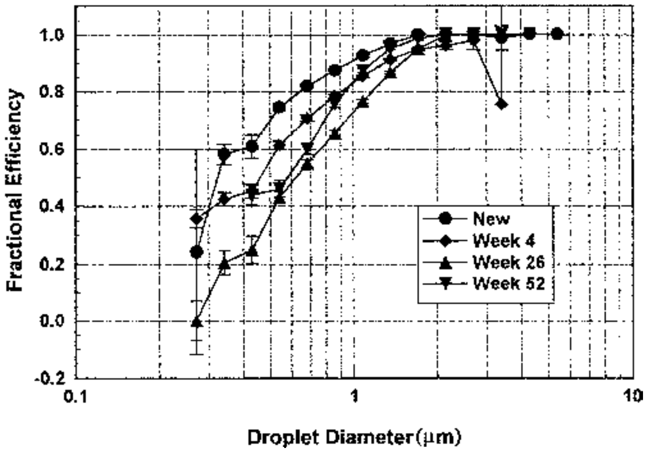

FIGURE 3
Efficiency vs. droplet diameter for the 10-pocket filter in the plant collecting hobbing oil mist when new and over time.

RESULTS

Figures 2–6 describe trends in penetration with droplet size over time and are representative of the results obtained. In general, the performance of a given collector component did not depend strongly on the composition of the mist collected; however, some exceptions to this situation were found, as described below.

Efficiencies of First-Stage Filters

Figure 2 shows efficiency versus droplet diameter for two first-stage filters, the metal mesh filter and the wire mesh filter, when tested in the laboratory with soluble oil mist. The efficiencies of the metal mesh and the wire mesh filters remained constant over time, both in the laboratory and in the plant. The metal mesh filter, used in all studies except #3d, was ineffective for droplets smaller than 1 μm but collected essentially all droplets larger than about 3.5 μm in diameter. The wire mesh filter, used in Study #3d, was also ineffective on droplets smaller than 1 μm but collected droplets larger than about 6 μm with high efficiency.

Efficiencies of Second-Stage Filters

Figures 3, 4, and 5 present the efficiencies of the four second-stage filters: the pocket filter from studies #1, 2, and 3a, the 95 percent and 65 percent cartridge filters from studies #3b and 3c, and the cartridge-wrap filter from Study #3d. Data in Figure 3

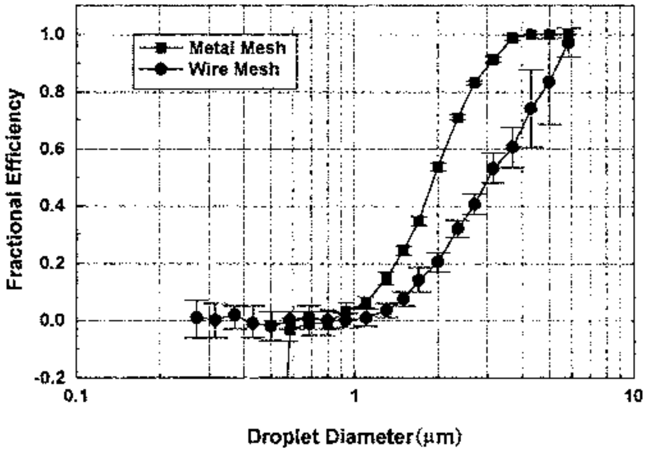

FIGURE 2
Efficiency vs. droplet diameter for metal mesh filter and wire mesh filter in the laboratory collector when tested with mist of soluble oil.

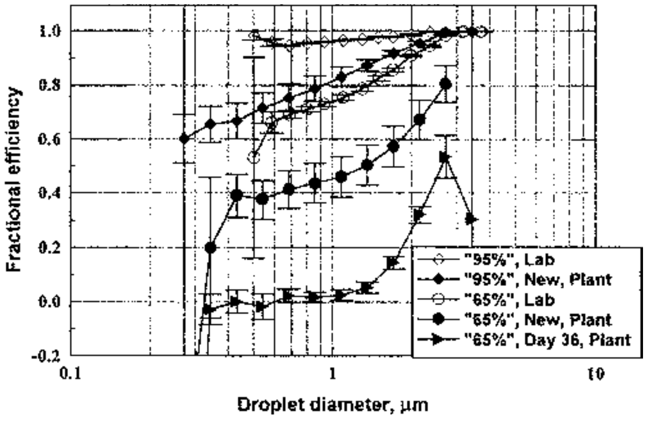

FIGURE 4
Efficiency vs. droplet diameter for a “95 percent” cartridge filter and a “65 percent” cartridge filter in the laboratory when collecting soluble oil mist and in a plant collector when collecting semi-synthetic mist, both new and over time.

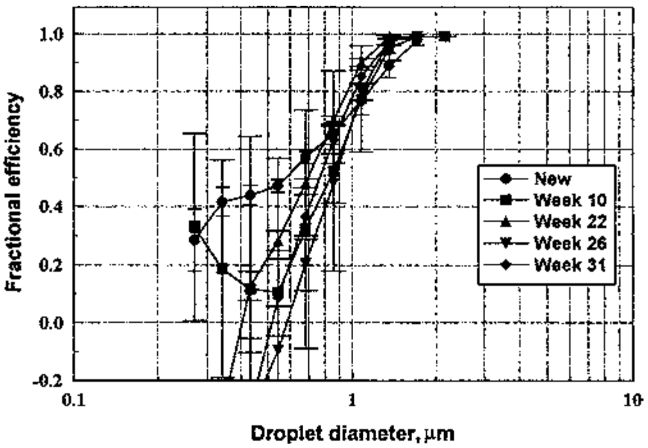

FIGURE 5
Efficiency vs. droplet diameter for the cylindrical cartridge filter and wrap when collecting semi-synthetic mist in the plant, over time.

present the efficiencies of the pocket filter in the plant collector when challenged with hobbing oil mist when the filter was new and after 4, 26, and 52 weeks of operation. During the first 4 weeks of the study, the efficiency of the pocket filter in the plant decreased considerably, especially for droplets less than 1 μm. This decrease leveled off at approximately 26 weeks, leaving the filter in a steady-state condition through 52 weeks of testing. The initial decrease in efficiency of the pocket filter followed by a steady-state performance for an extended period, as shown in Figure 3, was also observed in the laboratory tests with hobbing oil in Study #1, the laboratory and plant tests with soluble oil in Study #2, and the plant tests with semi-synthetic fluid in Study #3a.

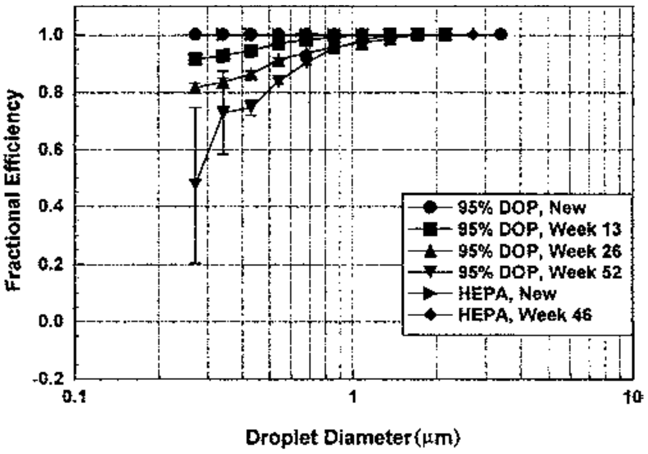

FIGURE 6
Efficiency vs. droplet diameter for 95 percent DOP filter in the plant collecting hobbing oil mist, and for a HEPA filter in the plant collecting soluble oil mist, over time.

The data in Figure 4 represent performance of new 95 percent and 65 percent cartridges from studies #3b and 3c when challenged with soluble oil mist in the laboratory and semi-synthetic mist in the plant; data for the performance of the 65 percent cartridge after 36 days of operation in the plant are also presented. Neither cartridge performed as well when challenged with semi-synthetic mist in the plant as when challenged with soluble oil mist in the laboratory. After 14 days of operation, plant engineers shut down the collector with the 95 percent cartridge. This cartridge had gained 1.4 kg, and its pressure drop had increased sufficiently to clog the filter and allow only one-tenth the rated airflow through the collector. After 36 days of operation, Figure 4 shows that the efficiency of the 65 percent cartridge filter in the plant had decreased substantially for droplets of all sizes. As a result, the third-stage HEPA filter that followed the 65 percent cartridge filter gained 2.5 kg and plugged so that the fan could no longer draw the required air through the collector. Thus, although the 65 percent cartridge filter did not itself plug, its efficiency decreased enough to cause the HEPA that followed to overload and plug.

The data in Figure 5 represent efficiency performance of the cylindrical cartridge-wrap filter in Study #3d when new and after 10, 22, 26, and 31 weeks of operation. The efficiency of this second-stage filter increased during the 31-week study for semi-synthetic droplets larger than about 1 μm, but decreased for droplets less than 1 μm.

Efficiencies of Third-Stage Filters

Figure 6 shows efficiency against droplet diameter for the third-stage filters: a 95 percent DOP filter used in Study #1 in the plant when challenged with hobbing oil mist and a HEPA filter when challenged with soluble oil mist at the plant in Study #2. Data represent filter efficiency when new and after 13, 26, and 52 weeks of operation for the 95 percent DOP filter and performance when new and after 46 weeks for the HEPA filter. This figure shows that the efficiency of the 95 percent DOP filter decreased steadily with time for droplets less than about 1 μm in diameter.

Figure 6 shows the HEPA filter removed all detectable droplets throughout the entire testing period. Plant as well as laboratory data from Study #2 with soluble oil generally support this finding. In Study #3a, the HEPA maintained excellent efficiency throughout the 19-week test period, but its efficiency for droplets in the 0.7 to 1.1 μm range dropped slightly from 100 percent to 98 percent from week 10 onwards.

Pressure Drop and Component Loading

Pressure drop data for the filter components used in each study are listed in Table II. In most studies, pressure drops increased with time. Pressure drops are given when the components were new and at the conclusion of the study; duration of the study is also listed.

TABLE II
Pressure drop in inches of water across mist collector components. In each cell, the first number is pressure drop when installed, and the second number is pressure drop at the end of the study

	Empty housing	Stage 1	Stage 2	Stage 3	Entire collector	Duration weeks
Study #1						
Laboratory	2.30–2.40	0.55–0.55	0.40–1.40	0.40–0.55	3.65–4.90	52
Plant	3.10–4.20	0.30–0.40	0.60–2.20	0.10–6.00	4.10–12.8	52
Study #2						
Laboratory	2.25–2.55	0.65–1.10	0.35–3.65	0.80–1.80	4.05–9.10	52
Plant	2.05–2.15	0.30–0.45	0.30–3.35	0.90–1.30	3.55–7.25	52
Study #3a	1.40–1.65	0.20–0.40	0.50–2.05	1.00–3.65	3.10–7.75	22
Study #3b	1.70	0.30	0.30	1.20	3.50	2
Study #3c	1.80–2.00	0.30–0.30	0.15–0.30	1.55–>15.0	3.80–>15.0	5
Study #3d	3.40–3.70	0.15–0.15	0.25–2.50	0.45–2.00	4.25–8.35	31

In Figure 7, pressure drop is plotted against time for the metal mesh, pocket, and 95 percent DOP filters used at the plant when challenged with hobbing oil mist in Study #1. Figure 8 presents the weights of these same filters over time. Figure 7 shows that the pocket and 95 percent DOP filters operated at pressure drops that increased gradually through the year, while the metal mesh filter held steady. The rapid increase in pressure drop across the pocket and 95 percent DOP filters during the final month of the plant study may have been caused by high loadings of dust due to in-plant construction and renovation. Figure 8 shows that the metal mesh filter did not gain weight. The pocket filter increased in weight at a constant rate over the first half year, then maintained a constant weight thereafter. The weight of the 95 percent DOP filter increased at a constant rate throughout the study.

Data for increases in pressure drop and component weights were generally similar in all laboratory and plant studies that used the metal mesh filter, pocket filter, and a 95 percent DOP or HEPA filter. The metal mesh filter did not gain appreciable weight. The pocket filter increased in weight until it reached a steady-state loading of about 6 kg; at this point, loading became constant. In contrast, the 95 percent DOP and HEPA filters gained weight at constant rates, and did not reach steady-state loadings.

DISCUSSION

As mist collected on the components evaluated here, performance generally declined, efficiency sometimes decreased and, except for the first stage filters, pressure drop generally increased. Ultimately, performance decreases led to collector performance so unacceptable that the components had to be replaced. The purpose of each component in a multi-stage collector is to decrease the mist loading to the components that follow, to

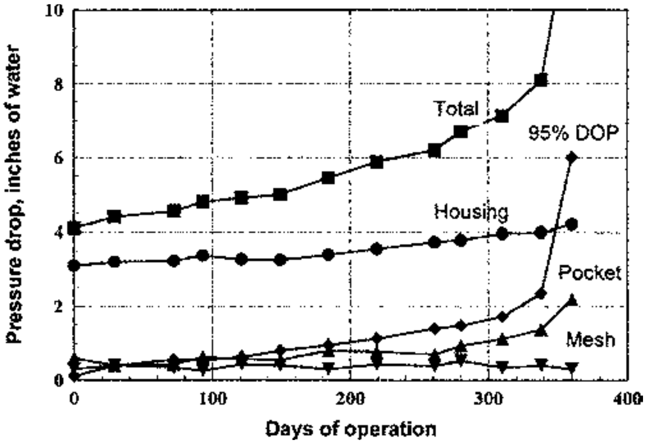

FIGURE 7
Pressure drop vs. operating time for each component of the collector used to control hobbing oil mist at the plant.

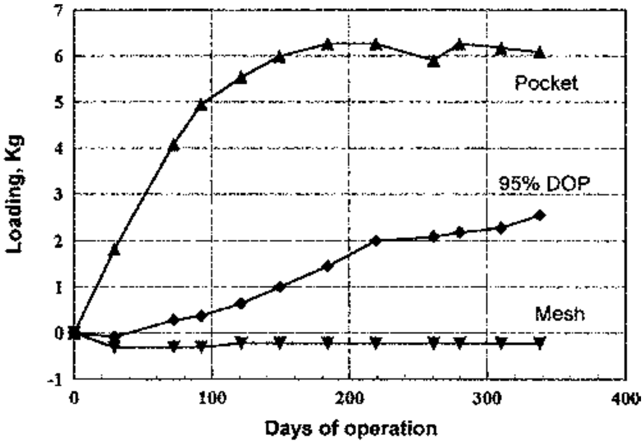

FIGURE 8
Component loading vs. operating time for each component of the collector used to control hobbing oil mist at the plant.

prolong their lives. Thus, a successful component will remove mist and whatever entrained solids may be present without a decrease in efficiency or an increase in pressure drop over time. Few components evaluated in these studies were successful by these criteria.

First-Stage Filters

The metal mesh and wire mesh filters used in these studies were steady performers and came closest to achieving success. They did not exhibit important changes in efficiency or pressure drop over time, in the laboratory or in the plant. Pressure drops for both first-stage filters were low. As shown in Figure 2, the metal mesh filter had somewhat higher efficiency than the wire mesh filter of Study #3d; Table II shows that the pressure drop of the metal mesh filter was somewhat higher as well.

Second-Stage Filters

Although the 10-pocket filters evaluated in these studies had good efficiency on sub-micrometer particles when they were new, their efficiencies for small particles decreased substantially over time both in the laboratory and in the plant, as shown in Figure 3. This efficiency decrease occurred during the time that loading on the pocket filter increased, as shown in Figure 8. Decreases in efficiency with liquid loading have been found previously in mist collectors,(17) as well as in studies with thin filter papers,(18) and in recent laboratory work with filter materials similar to those evaluated here.(19) In this laboratory work, the efficiency decrease was attributed to reduced collection of small particles by diffusion coupled with a decrease in the availability of collection sites, as the filter became loaded with liquid.(19) After the laboratory filter reached a critical mist loading, liquid drainage reached steady state.

Similarly, in the present studies, efficiency for the pocket filters initially decreased but then became relatively constant once loading became stable, as can be seen by comparing Figures 3 and 8. Somewhat surprisingly, the substantial increase in loading that occurred in the pocket filter during the first six months of these tests did not cause a correspondingly high increase in pressure drop (see Figure 7). These results suggest that the decrease in efficiency found for the pocket filter over time might be reduced if the filter could be redesigned to drain more effectively.

Figure 4 shows that the performance of the new 95 percent and 65 percent cartridge filters measured in the laboratory with soluble oil mist was not replicated under plant conditions with semi-synthetic fluid, even when new. Further, in the plant, efficiency for both cartridge filters decreased rapidly and substantially. The reason for the discrepancy between the relatively high efficiency found in the laboratory compared to the plant is not clear, but may be related to the test conditions. In the laboratory, efficiency tests took just a few minutes, whereas in the plant, these tests took several hours. Perhaps the additional mist loading that occurred while running tests in the plant reduced cartridge efficiency more quickly than expected. In any event, neither cartridge proved effective as a mist collector for long; each required replacement within a few weeks.

The cylindrical cartridge used in Study #3d, whose efficiency is shown in Figure 5, behaved similarly to the pocket filter described in Figure 3. Efficiency for submicrometer droplets again declined over time, whereas efficiency for droplets larger than 1 μm increased. Both effects may result from an increase in accumulated liquid in the filter over time. Retained liquid increases interstitial gas velocity, causing a decrease in collection efficiency by diffusion, important for smaller droplets, but also causing an increase in efficiency by impaction, important for larger droplets.(19) For the pocket filter, an increase in efficiency for larger droplets was not observed over time because efficiency was already high for droplets this size.

Third-Stage Filters

Figure 6 shows that the efficiency of the 95 percent DOP filter decreased over time, whereas the efficiency of the HEPA filter remained close to 100 percent for droplets of all sizes at all times. The effects of droplet loading should be less in HEPA filters because they contain more media than do 95 percent DOP filters, as shown in Table I. These results suggest that a HEPA filter is a better choice than a 95 percent DOP filter as a final stage filter. The HEPAs tested here always provided high efficiency even when pressure drops and loadings were high.

CONCLUSIONS

These results suggest that metal mesh filters work effectively under laboratory and plant conditions. Efficiency and pressure drop remained relatively constant over time for operating conditions that varied widely. The pressure drop across metal mesh filters is relatively low, so that additional performance improvements might be possible without a substantial increase in the overall pressure drop of the system.

Second-stage filters vary widely in performance. The 65 percent and 95 percent cartridge filters evaluated in studies #3b and 3c were unsuited for use in an industrial mist collector. Second-stage filters with more media, such as the cylindrical cartridge and the 10-pocket filter, had much longer lifetimes, but their efficiencies for submicrometer droplets decreased over time. Unfortunately, submicrometer droplets are particularly important because they are respirable. These results, taken in the context of previous work reported in the literature,(19, 20) suggest that the efficiency of second-stage filters can be maintained at a higher level if these filters can be modified to drain more effectively.

HEPA filters were effective as third-stage, final filters in all tests. Even after a year of operation in a difficult plant atmosphere, during which HEPA loading and pressure drop increased substantially, efficiency remained high even for submicrometer droplets. These results show that an industrial mist collector can be extremely effective at collecting metalworking fluid mist, as long as it uses a HEPA filter as the final collection stage. Whether the collector is successful from a more practical standpoint depends on the success of the stages upstream of the HEPA; these upstream stages reduce the loading and operating pressure drop of the HEPA, thus extending its life.

The conditions under which performance tests were conducted in these studies varied widely. Laboratory tests were conducted under idealized clean conditions, whereas tests in the transmission plant were often conducted under difficult conditions that taxed the collector components more severely than could be accomplished in the laboratory. Thus, trends identified by evaluations as diverse as these may reasonably be expected to transfer to other conditions as well.

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