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Model Development for the Design of Better Mist Filters

FINAL PERFORMANCE REPORT

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LIST OF ABBREVIATIONS

c_D particle concentration downstream from test filter

c_U particle concentration upstream from test filter

m_f mass of fibers comprising test filter

m_l mass of liquid within test filter

S saturation ratio

V volume occupied by test filter

α filter solidity

η filtration efficiency

ρ_f density of fiber material

ρ_l density of test fluid

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ABSTRACT

More than one million workers are exposed to metalworking fluid mists in the United States. Epidemiological studies indicate that exposure to these mists is related to respiratory ailments such as a chronic cough, bronchitis, and hypersensitivity pneumonitis and skin disorders such as dermatitis. Some research has suggested that exposure to metalworking fluid mists may be related to certain types of cancer, particularly those in the gastrointestinal tract. In workplaces, mist droplets are collected by local exhaust ventilation and the captured air is often passed through mist collectors containing filters before the cleaned air is recirculated to the workplace. Thus, the filters should be able to maintain flow through the system and collect as many droplets as possible. Prior research has shown that pressure drop increases and efficiency decreases for mist filters as they are used. The objective of this research was to determine if altering the kind of fibers used in a filter and the dimensions of a filter could be tools to make mist filters more effective than they are now.

The influence of fiber material on filter performance was evaluated by making test filters by hand from either glass fibers or polyaramid fibers. The filters were exposed to mist from bis(2-ethylhexyl) sebacate or a straight oil metalworking fluid until they reached a steady operating state. Pressure drop was monitored using a manometer while efficiency was measured using impactors. Results showed that the filters made from polyaramid fibers, which allowed liquid to spread and drain more easily, exhibited smaller increases in pressure drop at steady state than filters made from glass fibers. However, the reduction in efficiency was the same as liquid accumulated within filters made from both kinds of fibers.

The influence of filter height and thickness was measured by installing hand-made test filters in a new apparatus constructed for this project. Pressure drop was measured with a manometer while filtration efficiency was evaluated using a real-time particle sizing and counting instrument as the filter collected droplets from when it was clean until it achieved a steady operating condition. The data indicated that thinner filters accumulated more liquid per unit volume than thicker filters, particularly when the fiber diameter was small. Pressure drop increases were influenced only slightly by the thickness of the filter. Filter height did not affect filter performance at all. Filtration efficiency in these tests increased with time, unlike most of the prior studies. This increase may have occurred because of the high incoming mist concentrations used to accelerate the filter loading in these tests.

This study suggests that using alternative fibers with high surface energy may improve the performance of mist filters. In addition, more research may be warranted to develop equations to optimize the thickness and other properties of mist filters in order to achieve the best combination of efficiency and pressure drop.

SIGNIFICANT FINDINGS

Making filters from fiber materials with high surface energy, such as polyaramid fibers, allows collected mist droplets to spread easily across the surface of the fibers. Tests indicated that filters made from polyaramid fibers retained less liquid than filters made from glass fibers at the same test conditions. The polyaramid fibers allowed liquid to drain to fiber intersections and then through the filter more easily than glass fibers, which have a lower surface energy.

Using fibers that allowed liquid to drain more easily through a filter resulted in lower pressure drop across the filter when it operated at a steady state. Experiments showed that filters made from polyaramid fibers exhibited smaller absolute increases and percentage increases in pressure drop than filters made from glass fibers at the same test conditions.

Filters collecting mist droplets at low enough concentrations lost efficiency with time as they collected and accumulated liquid. Because filters made from polyaramid fibers retained less liquid when the filters operated at steady state, the researchers hoped that efficiency would not decline as much as it did with filters made from glass fibers. However, filters made from polyaramid fibers did not exhibit statistically smaller reductions in efficiency than filters made from glass fibers.

Tests on filters of varying dimensions showed that thinner filters accumulated more liquid per unit volume than thicker filters. This higher level of liquid saturation was particularly apparent for filters made from fibers having small diameters. In these filters, much of the liquid collected in the front portion of the filter because the filter was highly efficient. Filter height did not have a significant effect on liquid retention.

The pressure drop increase across filters collecting mist droplets was a strong function of the diameter of fibers in the filter. Filters made from small fibers exhibited much larger increases in efficiency than filters made from large fibers. However, the percentage change in pressure drop did not depend significantly on the fiber diameter. The percentage increase in pressure drop depended modestly on filter thickness: thin filters had a larger percentage increase than thicker filters. Pressure drop increase did not depend on filter height.

Most research has shown that filters collecting mist droplets exhibited efficiency decreases as they accumulated liquid. However, the tests conducted on filters with different thicknesses and heights showed mostly efficiency increases with loading. These increases may have occurred because the mist concentrations in this study were much higher than the concentrations used in most previous research. This finding suggests that mist concentration was a more important factor than previously believed in determining how a mist filter performed.

USEFULNESS OF FINDINGS

In these tests, filters made from polyaramid fibers, which had a relatively high surface energy, performed better when collecting mist droplets than filters made from glass fibers, which had a relatively low surface energy. If filters made from high surface energy fibers operate at lower pressure drops once they reach a steady operating state, workers and businesses can benefit. First, the utilization of energy by fans to move air through the filters might be less; businesses could save money. Second, a higher airflow could be maintained through the local exhaust ventilation system to which the mist collectors are attached. This higher airflow might gather mist droplets more effectively and protect workers more effectively from potentially hazardous metalworking fluid mist droplets. Further research is warranted to determine (1) if the benefits of high surface energy fibers on pressure drop through wetted filters is evident at mist concentrations more typical of those found in workplaces, (2) if smaller efficiency reductions are observed for fibers with high surface energy when the mist concentrations used to test the filters are similar to those found in real workplaces, and (3) if product-size filters exhibit the same benefits as small, custom-made test filters.

The findings of the filter dimension tests suggest that the thickness of the filter can play an important role in how the filter performs over its operating life. For example, choosing a less-efficient, thick filter may be a more effective strategy than using a more-efficient, thin filter. Unfortunately, the tests conducted in this study were probably run at such a high concentration that the efficiency changes measured do not reflect performance likely to be observed in real filters. More research measuring the performance of mist filters having different thicknesses when exposed to concentrations more typical of those found in real workplaces could help determine optimal designs for mist filters.

SCIENTIFIC REPORT

Background

Many industrial processes rely on fibrous filters as an economical way to separate liquid droplets from the air that workers breathe. Fibrous filters are utilized as mist eliminators in chemical plants during the production of compressed gases and acids (Brink et al., 1966; Brink et al., 1968). Stationary internal combustion engines, compressors, and turbines use filters to reduce emissions from lubrication oil reservoir vents (Belden and Roddy, 1994). Facilities with nuclear reactors employ high efficiency filters to protect workers and the public in case of accidents that may release radioactive coolant droplets (Burchsted et al., 1976). Workers wear respirators to protect themselves from many kinds of hazardous airborne mists (Woodside and Kocurek, 1997). Finally, machining operations use fibrous filters in mist collectors that are intended to remove droplets from air captured near metalworking machines (Leith et al., 1996).

The control of mists generated by machining operations is particularly important because the National Institute for Occupational Safety and Health (NIOSH) has estimated that more than 1.2 million people in the United States work with or near metalworking fluids (NIOSH, 1977). As metalworking fluids are poured or sprayed onto the tool and work piece, airborne droplets are generated by impaction on surfaces, ejection by centrifugal forces, and evaporation and recondensation in the surrounding air (Thornburg and Leith, 2000). Woskie et al. (1994) estimated that mass median droplet diameters are between 5.5 and 8.0 μm and geometric standard deviations range between 2.4 and 3.3. Particles the size of metalworking fluid mist droplets can disperse throughout a workplace if not controlled properly.

Metalworking fluid (MWF) exposures are associated with a variety of adverse health effects, most commonly skin disorders such as irritation, rashes, oil acne, dermatitis, folliculitis, and keratosis. Eye, nose and throat irritation, and respiratory disorders such as breathing problems, changes in respiratory function, coughing, asthma, lipid pneumonia, hypersensitivity pneumonitis, chronic bronchitis, and tightness of the chest are also common health effects associated with exposure to MWFs. Some MWFs are associated with an increased risk of larynx, rectum, pancreas, skin, scrotum, and bladder cancers (NIOSH, 1998).

To reduce worker exposure to potentially harmful droplets, companies often surround metalworking machines with hoods or enclosures to exhaust mist-laden air before the droplets can enter workers' breathing zones. Fans draw the contaminated air through ducts to mist collectors that are supposed to remove droplets with high efficiency. Air leaving the collectors is usually recirculated to the workplace to avoid tempering the make-up air that would be necessary if these high-volume flows were exhausted outside. The recirculation requirement means that the mist collectors must remain effective at all times to prevent elevated exposures to potentially harmful mists.

Many types of mist collectors are available commercially (Leith et al., 1996). Typically, collectors are comprised of multiple stages with each successive stage intended to eliminate smaller droplets. Early stages remove large droplets with baffles, a roughing filter, a centrifugal collector, or an electrostatic precipitator. The later stages are usually filters such as deep fiber

beds, hanging pocket filters, or thin pleated filters such as 95% dioctyl phthalate (DOP) or High-Efficiency Particulate Air (HEPA) filters.

When filters collect dry particles, their efficiency increases with time (Brown, 1993). However, as filters installed in mist collectors collected liquid droplets, Leith et al. (1996) showed that filtration efficiency *decreased* with time. Other studies have yielded similar results for thin filter papers and Ultra-Low Penetration Aerosol (ULPA) filters (Kolganov and Radushkevich, 1967; Mohrmann, 1970; Mohrmann and Marchlewitz, 1974; Bergman et al., 1985; Payet et al., 1992; Raynor and Leith, 2000). In addition, the pressure drop increases as liquid collects on the mist filters. When efficiency reductions occur in machine shops, two important problems may occur that are detrimental to worker health. First, the amount of mist being recirculated to the workplace from the collector may increase if the final filter loses efficiency with time. The efficiency reduction may, therefore, result directly in an increase in worker exposure to potentially hazardous droplets. Second, if the preliminary filter stages lose efficiency faster than expected, they may expose final filters to higher concentrations of mist that will load the final filters with liquid rapidly. As final filters are loaded with liquid, the pressure drop across the filters increases dramatically. With the increase in pressure drop, the airflow through the ventilation system will decrease. This decrease in flow may allow more droplets to evade capture in the hoods and enclosures, causing increases in worker exposures to the mist. In either of these two scenarios, filters must be replaced frequently in the collector to avoid substantial increases in MWF mist exposure.

Raynor and Leith (1999, 2000) developed models to predict the performance of wetted filters. These models included the processes of filtration, evaporation of the liquid, and drainage through the filter. Predictions for changes in liquid retention, pressure drop, and filtration efficiency are produced by the models. The models included input on filter and operating parameters such as fiber diameter, filter solidity, incoming mist concentration and size distribution, and filtration velocity. However, the models were developed under the assumption that the liquid saturation is equal at all locations within a filter. Although Raynor and Leith (2000) observed that liquid retention did not vary much with height, the acceptability of the models for any filter height was not demonstrated thoroughly. In addition, Raynor and Leith observed that liquid retention was not constant with filter depth, particularly for highly efficient filters that collect most of the incoming mist near the front surface of the filter. Thus, the models could be improved by adding terms that account for changes in filter performance as a function of filter height and thickness. In order to understand those dependencies more thoroughly, experimental data is required.

In addition to variation in filter dimensions, changes in fiber material may be able to influence the performance of mist filters. For example, coatings may be applied to common glass fibers or polymer fibers may be used in filters. Opportunities may be available to select fibers for mist filters that will allow retained liquid to drain more rapidly from the filter. If the liquid drains from the filter more effectively at lower liquid retention levels, the efficiency reductions and pressure drop increases should be minimized.

In previous experiments reported by Raynor et al. (2000), individual fiber types were photographed microscopically as they were exposed to high mist concentrations to see how liquid was retained. The total length of fibers in the images was measured and the drops were

counted. The ratio of number of drops divided by fiber length was calculated to give a “drop density” in drops/cm. The results of these experiments showed that liquids spread more readily on individual polyaramid fibers than on glass fibers, and that retained droplets grew only at fiber intersections for polyaramid fibers, versus accumulating all along individual glass and polyester fibers. This spreading suggests that filters made from polyaramid fibers will drain more quickly and retain less liquid at a steady operating state. Because they may retain less liquid, filters made from polyaramid fibers may be less likely to exhibit substantial efficiency losses and pressure drop increases when collecting liquid droplets. To determine the influence fiber materials may have on mist filtration, further tests are needed to measure changes in efficiency and pressure drop on filters manufactured from different fiber types.

Specific Aims

To make the Raynor and Leith (2000) model more useful as a design tool, the model should be extended so that the performance of filters made from many types of fibers and with any thickness can be predicted. To accomplish this goal, laboratory experiments were conducted to measure changes in filter performance as filter dimensions and materials were altered.

Specifically, the proposed research had the following aims:

- (1) Based on the experience of Raynor and Leith (2000), design an improved test apparatus to measure the mist collection performance of custom-made test filters,
- (2) Conduct a set of experiments to study the influence of fiber material on mist filter performance,
- (3) Conduct a set of experiments to determine the effects of filter thickness and height on mist filter performance, and
- (4) Combine the data collected from these experiments with data from earlier studies to develop an improved mist filter model.

With improvements to the ability to predict the performance of mist filters, manufacturers should be able to optimize filters so that efficiency reductions and pressure drop increases can be minimized over the lifetime of a mist control filter. If the efficiency reductions are minimized or eliminated in real filters, workers will have less exposure to mists that may harm their health.

Methods

Aim #1: Design an improved test apparatus

Figure 1 is an image showing the apparatus designed and constructed for this project. The apparatus has three sections. Mist is introduced into the 30.5 cm x 30.5 cm x 61.0 cm chamber on the left and is mixed by the moving air. Air samples can be drawn from this chamber through a 30.5-cm long, 0.95-cm diameter probe. The test filter is placed in the small middle chamber. As mist-laden air is drawn through the test filter, liquid can drain from the filter through a valve in the bottom of this section. The chamber on the right in Figure 1 is for post-filter mixing and

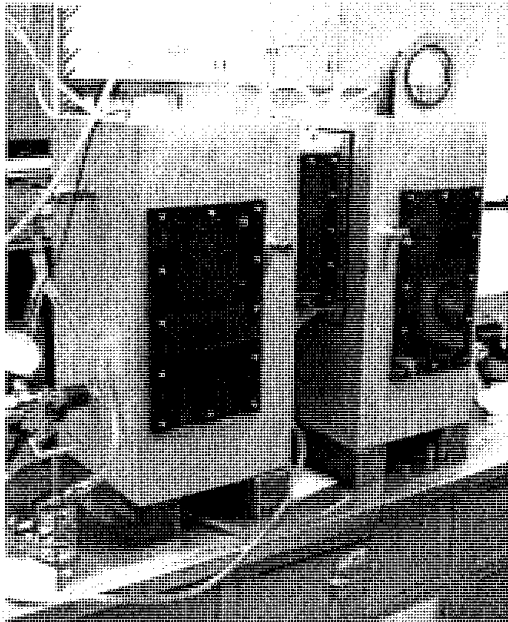


FIGURE 1: Apparatus constructed for improved mist filter testing.

filter was positioned. The test filter was inserted into the apparatus through removable plastic windows on either side of a 10.2-cm wide x 15.2-cm high x 7.6-cm deep stainless steel chamber. The bottom of the chamber consisted of a 7.6-cm long contraction leading to a drain with a closure through which liquid draining from the test filter could be drawn by a vacuum into a flask when the closure was opened. After leaving the chamber, the flow passed through a 10.2 cm long contraction into a 3.6 cm diameter pipe. Identical sampling probes entered the apparatus pre- and post-filter to obtain measurements of droplet counts upstream and downstream from the test filter.

The test filters were made by hand from either polyaramid fibers with an average diameter of $8.0\ \mu\text{m}$ or glass fibers with an average diameter of $8.5\ \mu\text{m}$.

The filters were formed by suspending fibers in a mixture of water and acetic acid, with a pH of approximately 3.0. The fibers were then poured into a $5.08\ \text{cm} \times 10.16\ \text{cm} \times 0.88\ \text{cm}$ filter holder, which was pre-weighed, and drawn by gravity through a fine mesh to form a fiber bed in which fibers were oriented randomly. The filter was then rinsed with deionized water and methanol to remove the acid and to prevent fiber bunching during the drying period. Wet fibers were then compressed into the holder so each filter had a final thickness of $0.88\ \text{cm}$. The filter holders had a coarse metal mesh on their downstream sides to prevent the filters from collapsing

sampling. A vacuum pump is located downstream from the final chamber. This new apparatus was utilized for the filter dimension tests, but not for the fiber material experiments.

Aim #2: Study influence of fiber material on mist filter performance

Figure 2 illustrates the apparatus used to expose the filters to mist during experiments to evaluate the performance of complete filters made from different kinds of fibers. Room air was drawn by a vacuum pump through a high efficiency filter, through a calibrated orifice for flow measurement, into tubing, and then into a section of PVC pipe. Mist from a three-jet Collison nebulizer (BGI, Inc., Waltham, MA) was introduced into the flow via the pipe before the air returned to more tubing. The flow then entered a 30.5-cm long stainless-steel expansion that ended in a $5.1\ \text{cm} \times 10.2\ \text{cm}$ opening, where a test

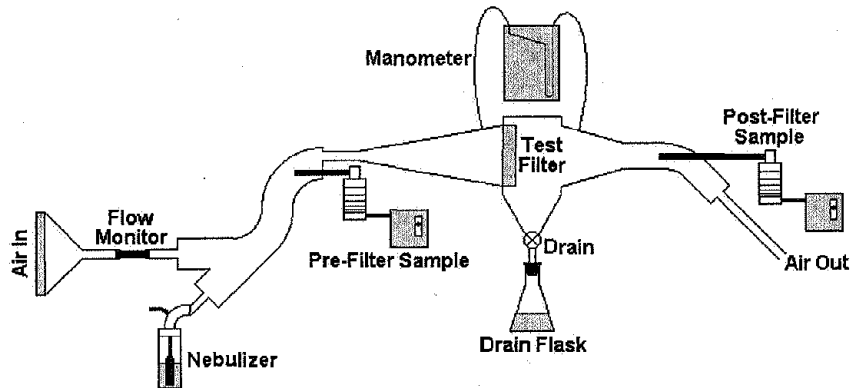


FIGURE 2: Apparatus used to test filters made from different fiber materials.

during the tests. A braided 0.95 cm diameter glass fiber wick was pre-weighed and incorporated into the filters to draw fluid reaching the bottom of the filter into the drain.

After the filter was dry, it was weighed and the solidity of the filter was calculated using the masses of the dry filter, wick, and holder and the density of the fiber. The solidity of the filter, α , was calculated using the equation

$$\alpha = \frac{m_f}{V \rho_f} \quad (1)$$

in which m_f is the mass of the fibers in the filter, V is the volume of the filter, and ρ_f is the density of the fibers. The density of the polyaramid fibers was 1.4 g/cm³ and the density of the glass fibers was 2.5 g/cm³. The solidity of the polyaramid fiber filters ranged from 0.049 to 0.050; the solidity of the glass fiber filters ranged from 0.044 to 0.050.

The nebulizer was used to generate mist from bis(2-ethylhexyl) sebacate (BEHS) and a straight mineral oil MWF (Ilocut 5468, Castrol, Downers Grove, IL). Filters were exposed to mists until they reached a steady operating state, which was considered to be when pressure drop was stable for at least 30 minutes and the drainage rate stopped increasing. For these tests, filters were exposed to the oil mist from five to nine hours. Liquid that drained from the filter was weighed throughout the tests to determine the drainage rate.

The amount of liquid retained within a filter is represented by S , the saturation ratio. S is the fraction of the void volume of a filter filled with liquid. The saturation ratio was calculated using the equation

$$S = \frac{m_l \rho_l}{V (1 - \alpha)} \quad (2)$$

in which m_l is the mass of the liquid trapped in the filter at steady state and ρ_l is the liquid density. The density of the straight mineral oil was 0.897 g/cm³. The density of BEHS was 0.914 g/cm³.

Pressure drop across the filter was monitored continuously during the tests using a Dwyer manometer (Dwyer Industrial, Michigan City, IN) attached to pressure taps upstream and downstream from the filter.

Size-specific efficiency measurements were taken using two Model 298 Eight Stage Marple Personal Cascade Impactors (Graseby Andersen, Smyrna, GA). The cascade impactor inlets were adapted to fit the sampling ports. The impactors were attached to GilAir 5 Tri-mode Constant Flow air sampling pumps (Sensidyne Inc., Clearwater, FL) operating at 2.0 L/min. The Marple Impactors were loaded with 34-mm diameter mylar collection substrates. These substrates were weighed pre- and post-sample to obtain particle size distributions and particle mass concentrations. Efficiency (η) of the filter was calculated for each particle size range using the following equation:

$$\eta = 1 - \frac{c_D}{c_U} \quad (3)$$

in which c_D is the particle mass concentration downstream from the filter and c_U is the particle mass concentration upstream of the filter. Efficiency measurements were taken at the beginning of the tests and after steady state had been achieved.

Most of the mist droplets that were generated for the experiments had diameters between 0.52 and 6.0 μm . The flow of air entering the filter was 32.5 liters per minute, which was equivalent to a face velocity of 10.5 cm/s. The average mist concentration generated by the nebulizer was 2,560 mg/m^3 . Most industrial mist collection systems would have a mist concentration of less than 10 mg/m^3 (Boundy et al., 2000). Such a high concentration was chosen to accelerate the saturation of the filters.

A total of 12 tests were conducted. Three tests were conducted with glass fiber filters and straight oil, three with glass fiber filters and BEHS, three with polyaramid fiber filters and straight oil, and three with polyaramid fiber filters and BEHS. The first four tests conducted used one of each fiber and fluid combination. The order of the final eight tests was random.

Aim #3: Study effects of filter dimensions on mist filter performance

The apparatus in Figure 1 was utilized to study the effects of filter dimensions upon mist filter performance. Sixteen experiments were conducted in a factorial design to study the influence of fiber diameter, filter thickness, and filter height on the amount of liquid retained in the filter, the pressure drop across the filter, and the filter efficiency. Filters made from glass fibers with average diameters of 2.9 μm and 8.5 μm were included in the study. Four filter thicknesses were considered: 0.61, 0.95, 1.57, and 2.79 cm. Filter heights included 10.2 and 20.3 cm. Each combination of fiber diameter, thickness, and height was tested a single time.

Filters were created by hand in the laboratory. An appropriate mass of fibers was suspended and mixed in water. The pH of the water was adjusted to approximately 3.0 to disperse the glass fibers readily. The fiber suspension was poured into a funnel that contained a holder backed by a fine mesh in which a filter formed as the water drained through the mesh. A fiberglass wick was set into the holder before the suspension was poured into the funnel. The wick was included to allow for the eventual drainage of test fluid from the filter. A coarse mesh was incorporated into the downstream side of the holder to prevent the filter from collapsing when it was installed into the test apparatus. After water drained through the funnel, the wet filter was rinsed with deionized water and methanol, compressed to fit evenly into the holder, removed from the funnel, and allowed to dry. The dried filter was weighed and the solidity of the filter was calculated according to equation (1) by comparison of the complete filter mass to the initial mass of the empty holder and wick.

The filter for each test was mounted in the small central chamber shown in Figure 1. Air was drawn into the apparatus by a vacuum pump through four parallel HEPA capsule filters. The air entered the upstream (left) chamber, which measured 61.0 cm tall by 30.5 cm wide by 30.5 cm deep. The flow rate was either 31 or 62 L/min, depending on whether the filter was 10.2 or 20.3 cm tall, to provide a velocity at the filter face of 10 cm/s. BEHS droplets were introduced into the upstream chamber using a six-jet Collison nebulizer (BGI Inc., Waltham, MA). The mist concentration was about 7.0 g/m^3 when the flow was 31 L/min and about 3.5 g/m^3 when the flow

was 62 L/min. Upon exiting the filter, the air moved into the downstream (right) chamber, which was also 61.0 cm tall by 30.5 cm wide by 30.5 cm deep. The passage between the filter chamber and the downstream chamber was a small hole across which the pressure drop was calibrated to the desired flow rate. Air leaving the downstream chamber passed to the vacuum pump.

Samples were drawn from the upstream and downstream chambers through 30.5-cm long, 0.95-cm diameter probes. The mist in the chambers was assumed to be mixed well. Visual observation of the buildup of mist confirmed this assumption. Before the beginning of the test and after 2, 4, and 6 hours of testing, the concentration of mist was lowered so that only a single jet was drawing liquid from the nebulizer through a tube attached to the bottom of the nebulizer stem. At this lower mist concentration, samples were drawn alternately from the upstream and downstream chambers at 5 L/min by an Aerodynamic Particle Sizer (APS) 3310 (TSI Inc., St. Paul, MN). The sample first passed through an Aerosol Diluter (TSI Inc., St. Paul, MN) to lower the concentration by a factor of 100 so that the counts would not overload the APS sensors. The APS counted and sized particles in real time. Each sample was taken for one minute. Four pairs of upstream and downstream readings of droplet sizes and concentrations were made during each set of efficiency measurements. The sum of the upstream and the sum of the downstream readings were compared according to equation (3) for each droplet diameter to calculate efficiency.

Pressure drop was recorded periodically by reading a manometer attached to pressure taps located upstream and downstream from the test filter. Flow was adjusted as necessary to keep a constant airflow rate even when the pressure drop across the filter increased.

During the tests, liquid drained from the filter. After liquid began to appear in the drain just downstream from the filter, the liquid was suctioned through a valve into a flask by a vacuum source every 30 minutes. The flask was weighed after each suctioning event and the rate of liquid draining from the filter was calculated.

The test continued for six hours of loading, interrupted only by the efficiency tests. In all cases, the filter reached a steady operating state defined by the pressure drop and drainage rate holding steady. After the test, the wet filter, the filter without the wick, and the wet holder without the wick or filter were all weighed and the saturation ratio, S , was calculated according to equation (2).

Aim #4: Develop an improved mist filter model

This aim was not achieved during the project. Incorporating information on fiber material into the existing models presented by Raynor and Leith (2000) was not possible. Further review of the literature regarding the forces that affect spreading showed that the interactions of fluids and flat surfaces are exceedingly complex, particularly when liquid may already be coating part of the surface. In addition, the curvature of the fiber surfaces plays a significant role in the spreading. Extending the information from the two fluids and two fiber materials used in this project to characterize other possible fluid/fiber interactions is not appropriate. Each fluid/fiber combination is probably best tested on its own.

As discussed below, results from the filter dimension tests indicated that efficiency increased in most instances rather than decreasing as indicated in previous studies. These findings were probably caused by use of too high a mist concentration that caused the filters to behave differently than filters collecting levels of mist found in real workplaces. Therefore, the results of these experiments were not suitable for inclusion in the existing wet filter models.

Results and Discussion

Aim #2: Study influence of fiber material on mist filter performance

Figure 3 shows the saturation ratios of the different combinations of glass or polyaramid fibers and BEHS or straight oil test fluids after the filters reached a steady operating state. This graph indicates that filters made from polyaramid fibers drained more readily and retained less liquid than filters made from glass fibers. A statistical analysis of the saturation ratio data showed that the difference between the fiber types was significant ($p = 0.0003$), whereas the difference between the fluid types was not significant ($p = 0.66$).

These results make sense when compared to the ability of liquid to spread on the fibers. Raynor et al. (2000) showed that liquids spread more readily on individual polyaramid fibers than on glass fibers, and that retained drops grew only at fiber intersections on polyaramid fibers rather than along the individual fibers. Figure 3 suggests that this spreading may occur in entire filters made of polyaramid fibers, causing these filters to drain faster and retain less liquid at a steady operating state than filters made from glass fibers.

Filters made from glass fibers had an average initial pressure drop of about 60 Pa; filters made from polyaramid fibers had an initial pressure drop of 37 Pa. Figure 4

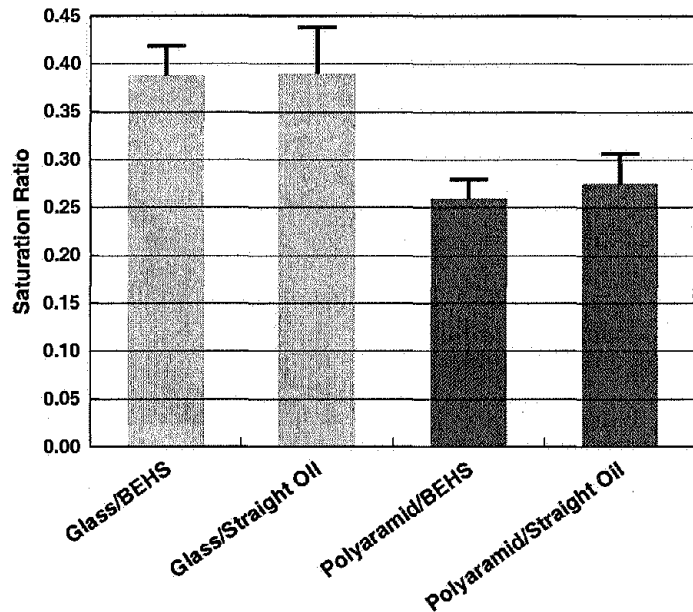


FIGURE 3: Average steady-state saturation ratios for mist filters made from glass and polyaramid fibers and tested with BEHS and straight mineral oil. Error bars represent one standard deviation.

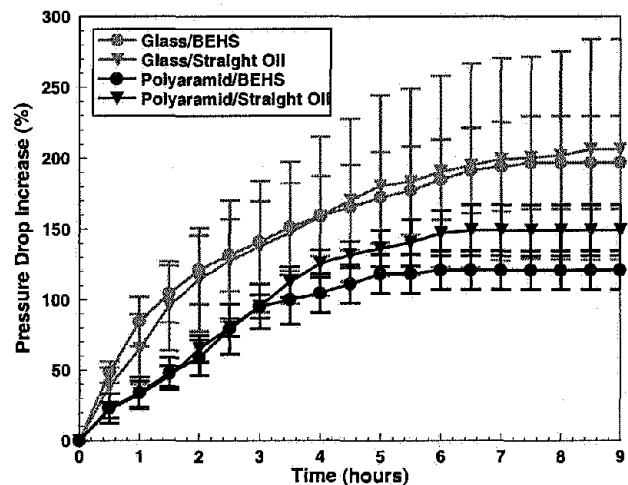


FIGURE 4: Pressure drop increase, in percent, versus time for mist filters made from glass and polyaramid fibers and tested with BEHS and straight mineral oil. Error bars represent one standard deviation.

shows the percentage increase in pressure drop across the filter during the tests for the various combinations of fiber type and test fluid. This graph indicates that filters made from glass fibers exhibited substantially higher percentage increases in pressure drop as liquid accumulated than filters made from polyaramid fibers. The absolute differences were even more pronounced because the glass fiber filters had a larger pressure drop initially. The difference in pressure drop increase between the polyaramid fiber filters and the glass fiber filters was significant statistically ($p = 0.0020$). The use of the different fluid types was not significant ($p = 0.82$).

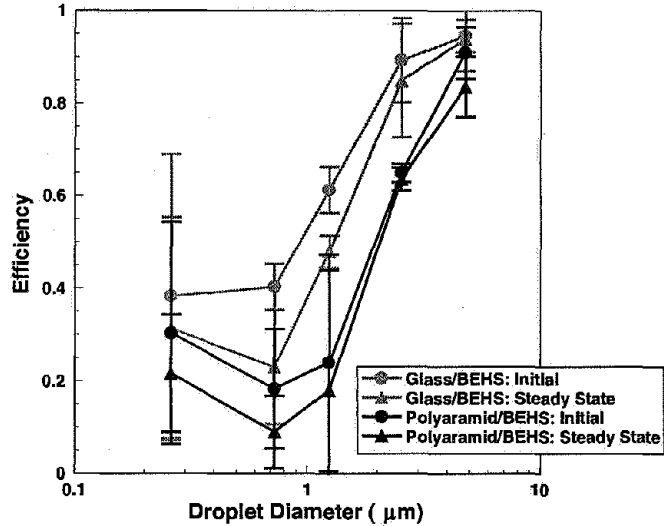


FIGURE 5: Initial and steady state filter efficiency as a function of droplet diameter for glass fiber and polyaramid fiber filters tested using BEHS.

These results are important from a filter performance standpoint. Boundy et al. (2000) and Raynor and Leith (2000) pointed out that an increase in pressure drop through mist filters can cause the airflow through the entire ventilation system to decrease to the point where hoods and enclosures cannot capture the droplets adequately. Therefore, making filters out of polyaramid fibers might lead to smaller pressure drop through mist filtering equipment and help to ensure that these ventilation systems capture mist droplets adequately when the filters are wet, as well as when they are new.

Figure 5 shows the efficiency for the glass and polyaramid fiber filters when clean and after collecting BEHS droplets until the filters reached a steady operating state. The efficiency declined for filters made from both kinds of fibers. Although the decrease in efficiency was

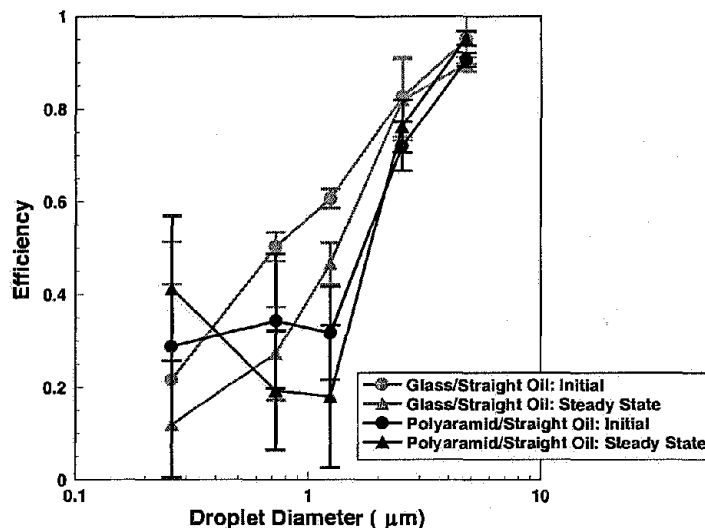


FIGURE 6: Initial and steady state filter efficiency as a function of droplet diameter for glass fiber and polyaramid fiber filters tested using a straight mineral oil.

slightly larger for the glass fiber filters for most particle sizes, the difference between the fiber types was not significant statistically. Figure 6 displays efficiency results for the filters that collected straight oil droplets. Again, differences between the fiber types were not significant. The statistical analysis also indicated that differences between the test fluids were not significant.

These results do not show hoped for minimizations in filter efficiency reduction. Specifically, the tests do not indicate that the polyaramid

fiber filters, which retained less liquid than the glass fiber filters, had smaller reductions in efficiency than the glass fiber filters. However, the wet polyaramid fiber filters might still be preferable to the glass fiber filters because they exhibited less of a pressure drop increase.

The test results may have been influenced some by differences between the glass and polyaramid fiber filters. Although the filters looked similar visually and had similar solidities, the polyaramid fiber filters had somewhat lower initial pressure drop and efficiency than the glass fiber filters. The influence of this difference on the tests was considered as the data was analyzed by conducting analyses on percent change in pressure drop and percent change in calculated single fiber efficiency. However, the different initial behavior may still affect the results in ways not considered during the data analysis.

Aim #3: Study effects of filter dimensions on mist filter performance

Saturation ratio and pressure drop results for the tests on filter dimensions were analyzed statistically to determine factors that were significant. For saturation ratio, the results showed that the fiber diameter, filter thickness, and the interaction between fiber diameter and filter thickness were significant statistically. However, the influence of filter height was not

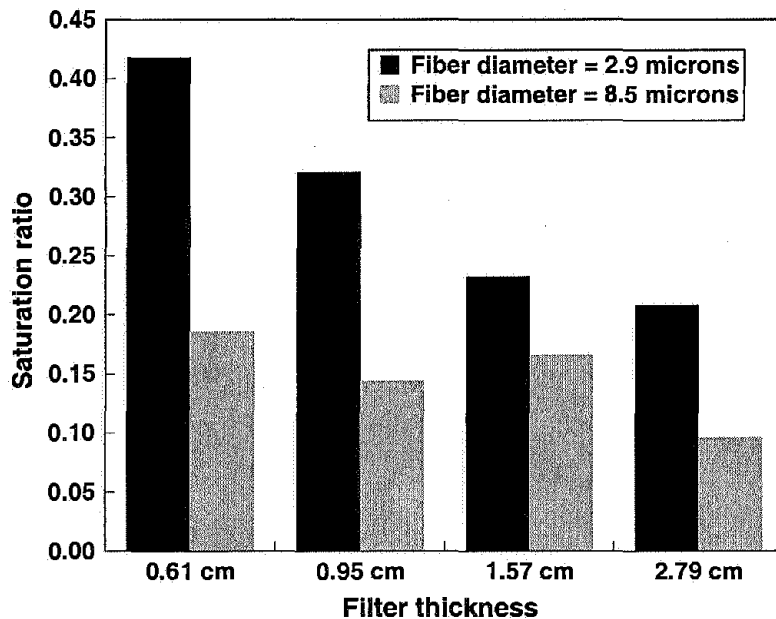


FIGURE 7: Saturation ratio as a function of mist filter thickness for glass fibers 2.9 and 8.5 μm in diameter.

significant. Figure 7 shows the influence of filter thickness on saturation ratio. The saturation ratio was highest for thin filters, particularly when the fiber diameter was small. This quantitative result is similar to visual observations reported by Raynor and Leith (2000). The saturation ratio was higher in thinner filters, and probably higher in the front sections of thicker filters, because droplets collect more rapidly within thin filters and in the front portions of thicker filters.

The only factor that influenced absolute increases in pressure drop significantly was the fiber diameter. The filter dimensions

did not have a statistically significant impact on the absolute pressure drop rise. For the fibers 2.9 μm in diameter, the average pressure drop increase was 1,560 Pa. However, for fibers 8.5 μm in diameter, the average pressure drop rise was only 172 Pa.

Raynor and Leith (2000) found that analyzing the ratio of wetted filter pressure drop to clean filter pressure drop instead of absolute pressure drop was a more effective way to predict changes in pressure drop as liquid accumulated within filters. When the data collected here were

analyzed as pressure drop ratios, fiber diameter was no longer a significant factor. In fact, filter thickness was the only significant factor ($p = 0.0285$). Filters 0.61 cm thick exhibited a pressure drop increases averaging 600 % whereas thicker filters exhibited pressure drop increases averaging only 290 %. This larger percentage increase occurred for both fiber diameters.

The efficiency results yielded the biggest surprise among the data. Instead of showing efficiency reductions as had been seen by other authors, the data almost uniformly showed efficiency increases with liquid loading similar to the example shown in Figure 8. The reasons for these increases are not certain. One likely

cause may be the high mist concentrations used in this study. Although Raynor and Leith (2000) used elevated concentrations nearing 1 g/m^3 , they did not use concentrations as high as 3.5 and 7.0 g/m^3 . These results suggest that high concentrations of mist may overload the front portions of filters with too much mist before the liquid has time to drain adequately through the filter. An artificially high level of liquid may contribute to unusual droplet collection mechanisms such as impaction caused by air bubbling through liquid and collection on liquid surfaces rather than fiber surfaces.

Aim #4: Develop an improved mist filter model

Although the reasons for the efficiency increases in the filter dimension tests are unclear, they were not the results anticipated during the design of this study. Therefore, the model development anticipated as part of the research proposal could not be accomplished. The authors are still considering how to include the information developed in this study into the theory of wetted filter collection. A logical next step in the research might be to conduct similar studies for a longer time at lower mist concentrations to determine if the expected efficiency reductions are observed.

Conclusions

Tests were conducted to determine if using filters made from polyaramid fibers, on which liquid spreads easily, to collect mist droplets rather than filters made from traditional glass fibers could lead to less liquid retention, smaller increases in pressure drop, and smaller efficiency reductions. The results showed that polyaramid fibers exhibited less liquid retention and smaller increases in

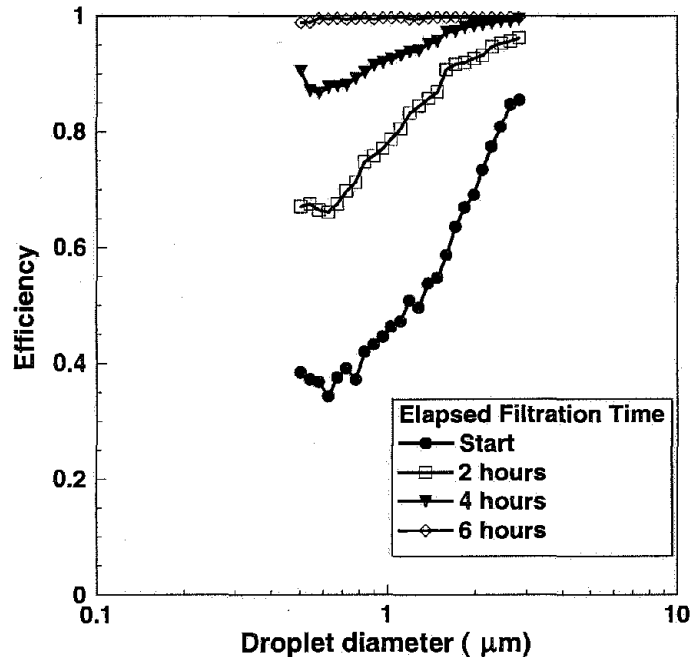


FIGURE 8: Efficiency as a function of droplet diameter for tests conducted on a filter 0.95 cm thick, 10.2 cm high, and made from glass fibers $8.5 \mu\text{m}$ in diameter. Data are shown for the initial efficiency and after 2, 4, and 6 hours of mist loading.

pressure drop than fiberglass filters. However, no statistically significant differences in efficiency reduction between the fiber types were noted during the experiments. These findings suggest that filters made from fibers with high surface energy may be advantageous for use in mist filters because they may lead to less accumulation of liquid in filters, which results in a smaller increase in pressure drop. This smaller pressure drop rise would lead to longer filter lifetimes and allow high airflow to be maintained through hoods or enclosures surrounding metalworking and other industrial processes that generate potentially hazardous mist droplets.

The use of alternative fiber materials should be studied further. A greater selection of fibers might be investigated in tests with lower concentrations of incoming mist to determine if fiber material can influence efficiency at mist levels found typically in workplaces. In addition, filter manufacturers might be interested in creating product-size filters from different materials for laboratory testing.

A second set of tests investigated the influence of filter dimensions on wetted filter performance using a new apparatus designed and built for this study. The results of these tests showed that thinner filters had a higher average saturation ratio, and therefore more liquid retention, than thicker filters. Although filters with smaller fibers had larger absolute pressure drop increases than filters made from larger fibers, the pressure drop increase depended more on the initial pressure drop than any other factor. The ratio of steady state wetted filter pressure drop to clean filter pressure drop varied only with filter thickness. Unexpectedly, these tests also showed increases in efficiency with liquid loading rather than efficiency reductions similar to those observed in most other studies. The efficiency increases may have occurred because of the high concentrations of mist utilized to load filters quickly during these experiments.

All of the data in the second set of tests indicated that filter height played little role in filter performance. Filter thickness, however, is a much more important parameter that should be investigated in further experiments at lower mist concentrations.

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STUDENTS SUPPORTED BY THIS PROJECT

Gina M. Letts, MS – Ms. Letts used data gathered as a Research Assistant on this project to write her Plan B paper that was required of her to complete her MS degree from the University of Minnesota.

Soo Jae Chae – Mr. Chae is currently a MS student in the University of Minnesota School of Public Health

Seung Won Kim – Mr. Kim is presently a PhD student in the University of Minnesota School of Public Health

PUBLICATIONS

No papers have been published from this research thus far. The findings from the experiments on different fiber materials for use in mist filters are clearly publishable. A manuscript by Gina M. Letts, Peter C. Raynor, and Rebecca L. Schumann entitled "Selecting Fiber Materials to Improve Mist Filters" has been prepared and is being edited for a final time by the authors before being submitted to the *Journal of Aerosol Science* for review and possible publication. The authors anticipate submitting this manuscript during the first week of February, 2003.

Publishing the results from the tests on filter dimensions will be more difficult. The results from this study will be combined with data from previous tests to describe the influence of mist concentration on the efficiency of wetted filters. The results may show that efficiency increases with loading for very high concentrations, but decreases with loading at lower concentrations. A manuscript on this subject will be prepared by mid-summer 2003 for submission to a filtration journal such as the *Fluid/Particle Separation Journal* or *Filtration and Separation*.



Memorandum

Date: March 18, 2003

From: Lee M. Sanderson, Ph.D., Program Official *Lee M. Sanderson*
Office of Extramural Programs, NIOSH, E-74

Subject: Final Report Submitted for Entry into NTIS for Grant 5 R03 OH004164-02.

To: William D. Bennett
Data Systems Team, Information Resources Branch, EID, NIOSH, P03/C18

The attached final report has been received from the principal investigator on the subject NIOSH grant. If this document is forwarded to the National Technical Information Service, please let us know when a document number is known so that we can inform anyone who inquires about this final report.

Any publications that are included with this report are highlighted on the list below.

Attachment

cc: Sherri Diana, EID, P03/C13

List of Publications

Title: Model Development for the Design of Better Mist Filters
Investigator: Peter C. Raynor, Ph.D.
Affiliation: University of Minnesota
City & State: Minneapolis, MN
Telephone: (612) 625-7135
Award Number: 5 R03 OH004164-02
Start & End Date: 8/1/2000–10/31/2002
Total Project Cost: \$68,526
Program Area: NORA
Key Words: control technology, metalworking fluids, engineering Controls

Final Report Abstract:

More than one million workers are exposed to metalworking fluid mists in the United States. Epidemiological studies indicate that exposure to these mists is related to respiratory ailments such as a chronic cough, bronchitis, and hypersensitivity pneumonitis and skin disorders such as dermatitis. Some research has suggested that exposure to metalworking fluid mists may be related to certain types of cancer, particularly those in the gastrointestinal tract. In workplaces, mist droplets are collected by local exhaust ventilation and the captured air is often passed through mist collectors containing filters before the cleaned air is recirculated to the workplace. Thus, the filters should be able to maintain flow through the system and collect as many droplets as possible. Prior research has shown that pressure drop increases and efficiency decreases for mist filters as they are used. The objective of this research was to determine if altering the kind of fibers used in a filter and the dimensions of a filter could be tools to make mist filters more effective than they are now.

The influence of fiber material on filter performance was evaluated by making test filters by hand from either glass fibers or polyaramid fibers. The filters were exposed to mist from bis(2ethylhexyl) sebacate or a straight oil metalworking fluid until they reached a steady operating state. Pressure drop was monitored using a manometer while efficiency was measured using impactors. Results showed that the filters made from polyaramid fibers, which allowed liquid to spread and drain more easily, exhibited smaller increases in pressure drop at steady state than filters made from glass fibers. However, the reduction in efficiency was the same as liquid accumulated within filters made from both kinds of fibers.

The influence of filter height and thickness was measured by installing hand-made test filters in a new apparatus constructed for this project. Pressure drop was measured with a manometer while filtration efficiency was evaluated using a real-time particle sizing and counting instrument as the filter collected droplets from when it was clean until it achieved a steady operating condition. The data indicated that thinner filters accumulated more liquid per unit volume than thicker filters, particularly when the fiber diameter was small. Pressure drop increases were influenced only slightly by the thickness of the filter. Filter height did not affect filter performance at all. Filtration efficiency in these tests increased with time, unlike most of the prior studies. This increase may have occurred

NIOSH Closeout Summary with Publications

because of the high incoming mist concentrations used to accelerate the filter loading in these tests.

This study suggests that using alternative fibers with high surface energy may improve the performance of mist filters. In addition, more research may be warranted to develop equations to optimize the thickness and other properties of mist filters in order to achieve the best combination of efficiency and pressure drop.

Publications

No publications to date.