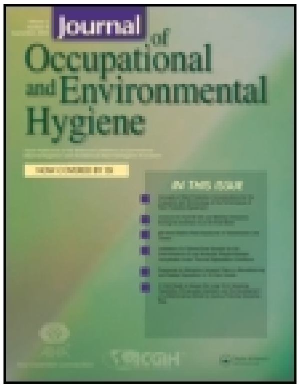

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Variation in Penetration of Submicrometric Particles Through Electrostatic Filtering Facepieces During Exposure to Paraffin Oil Aerosol

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Several studies show the increase of penetration through electrostatic filters during exposure to an aerosol flow, because of particle deposition on filter fibers. We studied the effect of increasing loads of paraffin oil aerosol on the penetration of selected particle sizes through an electrostatic filtering facepiece. FFP2 facepieces were exposed for 8 hr to a flow rate of 95.0 ± 0.5 L/min of polydisperse paraffin aerosol at 20.0 ± 0.5 mg/m^3. The penetration of bis(2-ethylhexyl)sebacate (DEHS) monodisperse neutralized aerosols, with selected particle size in the 0.03–0.40 µm range, was measured immediately prior to the start of the paraffin aerosol loading and at 1, 4, and 8 hr after the start of paraffin aerosol loading. Penetration through isopropanol-treated facepieces not oil paraffin loaded was also measured to evaluate facepiece behavior when electrostatic capture mechanisms are practically absent. During exposure to paraffin aerosol, DEHS penetration gradually increased for all aerosol sizes, and the most penetrating particle size (0.05 µm at the beginning of exposure) shifted slightly to larger diameters. After the isopropanol treatment, the higher penetration value was 0.30 µm. In addition to an increased penetration during paraffin loading at a given particle size, the relative degree of increase was greater as the particle size increased. Penetration value measured after 8 hr for 0.03-µm particles was on average 1.6 times the initial value, whereas it was about 8 times for 0.40-µm particles. This behavior, as well evidenced in the measurements of isopropanol-treated facepieces, can be attributed to the increasing action in particle capture of the electrostatic forces (Coulomb and polarization), which depend strictly on the diameter and electrical charge of neutralized aerosol particles. With reference to electrostatic filtering facepieces as personal protective equipment, results suggest the importance of complying with the manufacturer instructions when it is specified that their use has to be restricted to a single shift.

Keywords electrostatic filters, filtration, oil load, penetration, respirators

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INTRODUCTION

Filtering facepieces are frequently used in workplaces when personal protection by particle inhalation is needed.(1) Most commercially available facepieces are made of filtering materials with electrically charged fibers called "electrostatic filters."(2) An individual fiber can hold electric charges for years; it can possess a stable net electrostatic charge or can possess stable charges at different locations on the same fiber. For these reasons the electric field between the fibers is very strong even though the sum of the positive and negative charges across all the fibers is balanced.(3)

In electrostatic filters there are mainly two mechanisms of particle removal by electrostatic deposition: one is due to the Coulomb forces, the other is due to dielectrophoretic forces. The Coulomb forces operate between a charged particle and the opposite sign charges present on the fibers. The dielectrophoretic forces operate between particles polarized by the local electric field and the charges present on the fibers. These electrostatic mechanisms, working simultaneously with mechanical mechanisms (impact, interception, and diffusion) provide filtering materials with pressure drops lower than those of purely mechanical filtering materials having the same efficiency and superficial area.(4) This feature has encouraged the use of electrostatic materials in respirator filters to decrease breathing resistance and thereby make wearing particle-filtering respirators more acceptable to users.

Laboratory tests(5–10) showed that penetration through electrostatic filters increases with increased filter loading and that the increased penetration caused by the aerosol load is more evident for oily rather than for solid aerosols.(5,7,8) For oily aerosols the penetration increase was ascribed to the weakening of the electric field around the fibers caused by the spreading of the oily droplets on their surface.(7) There have been several studies of penetration and/or efficiency of electrostatic filters with loading, but few of them relate these properties to different test aerosol diameters. Baumgartner and Loffler[11] and Ji et al.[12] reported the change in efficiency of electrostatic materials during exposure to solid aerosols for test particles in the 0.01–5 μm range and for particles up to 0.5 μm. Chen et al.[13] reported the penetration values for three test aerosol diameters (namely, 0.16 μm, 1.19 μm, and 2.45 μm) measured during exposure to corn oil aerosol of filtering materials taken from facepieces.

The aim of the present study was to study the behavior of a commercially available electrostatic filtering facepiece exposed to increasing amounts of paraffin oil aerosol with reference to the effect on the penetration of submicrometric particles of different diameters.

MATERIALS AND METHODS

Eight commercially available FFP2 filtering facepieces of the same model were used. Samples were taken from the same lot to eliminate possible differences caused by inter-lot variability. The manufacturer recommended that the filtering facepiece respirator be replaced after one work shift.

Two different aerosols were employed: (1) a test aerosol of bis(2-ethylhexyl)sebacate (DEHS) used to measure penetration through the facepieces, and (2) a loading aerosol made of paraffin oil (Merkur, WOP 40 PB; Sasol Wax GmbH, Hamburg, Germany).

Filter penetration for selected particle sizes was measured by a fractional efficiency filter tester TSI 3160 (TSI Inc., Shoreview, Minn.) equipped with a filter holder especially structured to contain a filtering facepiece. The perimeter of the facepiece was glued around a shaped hole on a plate that was inserted in the filter holder, making it leak tight. The TSI 3160 uses three aerosol generators, a differential mobility analyzer (DMA), and two condensation nuclei counters (CNC) located, respectively, upstream and downstream of the facepiece being tested. Each aerosol generator together with the DMA produces a nearly monodisperse aerosol (σ_g < 1.3) that is neutralized (to the Boltzmann equilibrium) by a radioactive source of ^{85}Kr. The selected DEHS particle diameters were in the 0.03–0.40 μm range and the testing flow rate was 95±1 L/min. TSI 3160 gives an estimate of the penetration (evaluated as the ratio of the downstream to upstream mean number concentration) and of its 95% confidence interval.

To load the facepieces with known and reproducible amounts of paraffin oil, an aerosol generator (AGW/BM VI; Lorenz Messgerätebau, Katlenbury-Lindau, Germany) and an aerosol photometer (AP2E; Lorenz Messgerätebau), described in detail elsewhere,[10] were used. The generator produces a polydisperse aerosol of paraffin oil that is characterized by a mass median aerodynamic diameter of 0.47 μm with a geometric standard deviation of 1.82; it was set to produce an aerosol concentration of 20.0 ± 0.5 mg/m^3 at a flow rate of 95.0 ± 0.5 L/min. The facepiece was inserted in the filter holder following the same procedure described above. The aerosol photometer, gravimetrically calibrated, was used about every hour to check the constancy of the aerosol mass concentration during the facepiece exposure; moreover, it provided the penetration of the paraffin oil aerosol during filter exposure, calculated as the ratio of the aerosol concentration upstream to the concentration downstream of the respirator.

Two sets of measurements were performed. The first set was designed to assess the effect of increasing loads of paraffin aerosol on penetration; each of three facepieces was exposed to the paraffin oil aerosol for 8 hr. Penetration values of DEHS aerosols of selected diameters were measured before the beginning of the exposure and after 1, 4, and 8 hr, interrupting the exposure for the time strictly necessary for the penetration measurements. Two more facepieces were used as controls to assess the possible effect on the penetration of the airflow used during the exposure; they were subjected to the same measurement procedure applied to the facepieces exposed to paraffin oil, but in this case the airflow from the aerosol generator did not contain paraffin particles. This procedure also permitted us to independently assess the potential effect on DEHS penetration due to previous exposures to the DEHS aerosol.

The second set of measurements, performed on three more facepieces that were not oil paraffin loaded, was carried out to assess the influence of the electrostatic capture mechanisms on penetration. Each sample was dipped in isopropanol (IPA) for 60 min and then allowed to air dry for 24 hr. The IPA treatment is regarded as particularly effective in removing most of the electrostatic charges from the fibers. Because the isopropanol treatment did not change the structure of the filter,[2] the treatment allowed us to study the performance of the filter due to primarily mechanical filtration mechanisms.[2,9,13,14] DEHS penetration before charge removal was estimated calculating the mean of the initial (before loading) penetration ($\overline{P}_0$) of the same three facepieces employed in the first set of measurements, while penetration after electric charge removal was assessed by the mean of penetration ($\overline{P}_{IPA}$) of the three facepieces previously treated with IPA.

RESULTS AND DISCUSSION

The paraffin oil mass on the facepieces was 114, 156, and 912 mg after, respectively, 1, 4, and 8 hr of loading. Figure 1 shows the mean penetration values obtained from three tested respirators before the exposure to the flow of paraffin oil aerosol ($\overline{P}_0$) and after a time t of exposure ($\overline{P}_t$ for t = 1 hr, 4 hr, and 8 hr) in relation to the diameter of the test aerosol (DEHS). By increasing the exposure time, and consequently increasing the amount of paraffin oil deposited in the facepieces, the mean penetration gradually increases for all the analyzed aerosol diameters. Furthermore, the increase of the exposure time leads to a slight shift toward larger diameters of the most penetrating particle size.

Two facepieces used as controls did not show appreciable variation of the penetration after the exposure to the airflow with no paraffin oil.

These results show the effects of a progressive decrease of the electrostatic attraction caused by the deposition of oily material in the facepieces; the extreme case, where electrostatic

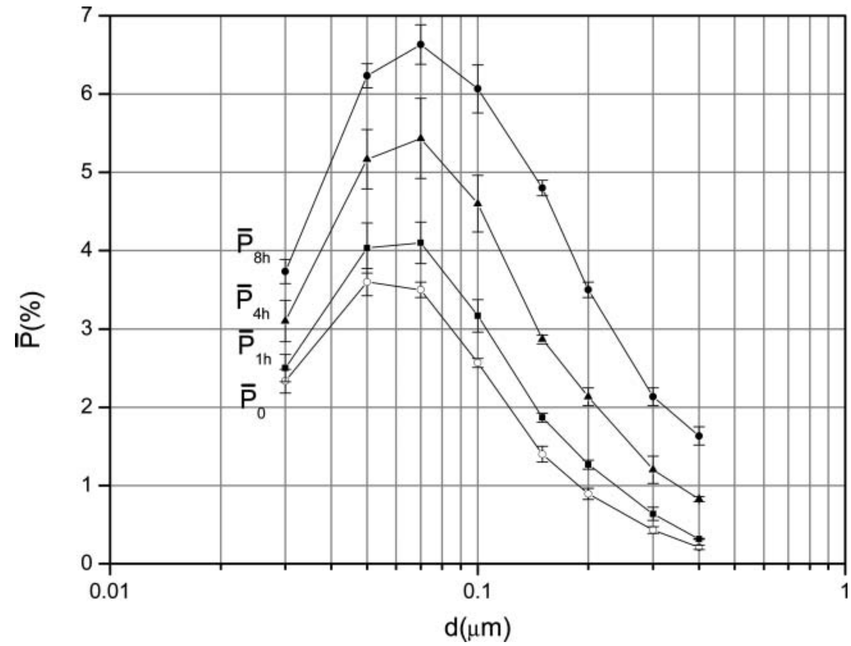

FIGURE 1. Neutralized DEHS aerosol mean penetration calculated through three filtering facepieces before ($\overline{P}_0$) and after different exposure times to paraffin oil aerosol ($\overline{P}_t$ for t = 1 hr, 4 hr, and 8 hr). The standard deviation bar is reported for each point.

capture mechanisms are absent and mainly mechanical mechanisms act in capturing particles, was studied by measuring the penetration through filtering facepieces treated with IPA.

Figure 2 reports the mean initial penetration values through three filtering facepieces ($\overline{P_0}$) and through three IPA-treated filtering facepieces ($\overline{P}_{IPA}$). As shown in Figure 2a, the most penetrating particle size for the non-IPA treated facepieces was 0.05 μm (about 3.7% penetration). Figure 2b shows that the most penetrating particle size for the IPA-treated facepieces was 0.3 μm (about 40% penetration). After the IPA treatment an increase in penetration can be observed for all the test aerosol diameters in accordance with the results reported by other authors.[14,15] The shift of the most penetrating particle size toward larger diameters after the charge removal from the fibers has been observed in other studies in which neutral or neutralized test aerosols (DOS, corn oil, and NaCl) were used.[7,13–15]

Note that although IPA treatment and paraffin oil loading both enhanced particle penetration as expected, the IPA treatment caused the greater increase in particle penetration. At 0.3 μm the mean penetration is about 2% after 8 hr of paraffin oil loading, while it is about 40% for IPA-treated facepieces. To sum up, the effects of the 8 hr paraffin loading and the effects of the IPA treatment are qualitatively the same: the penetration increase and the shift of the most penetrating particle size.

To compare the penetration increase observed for different sizes of the test aerosol after oil paraffin loading, penetration ratios ($\overline{P}_t/\overline{P}_0$) were calculated and plotted (Figure 3). For all the exposure times, the ratios $\overline{P}_t/\overline{P}_0$ increase with the size of the test particle. In particular, the ratio after the 8-hr exposure is 1.60 ± 0.07 for 0.03-μm particles and 8.2 ± 0.6 for 0.40-μm particles.

In analogy with oil-loaded facepieces, penetration ratios ($\overline{P}_{IPA}/\overline{P}_0$) of IPA-treated facepieces were calculated and plotted as a function of the test aerosol diameters in Figure 4 (top curve). The larger the diameter of the DEHS particle, the higher the penetration ratio. For example, the ratio for a 0.03-μm particle is 1.6 $\pm$0.2, whereas the ratio for a 0.40-μm particle is 157$\pm$10. For 0.03-μm particle size, the penetration ratio after the IPA treatment and the 8-hr exposure is the same (bottom curve in Figure 4 is a better comparison), whereas for all the other diameters it is greater for the IPA-treated facepieces with respect to the exposed ones.

A growing increase in penetration with the diameter after the charge removal was noted by other authors who tested electrostatic filters against neutral aerosols.[16,17] They observed that the contribution of the electrostatic forces caused by the polarization increases with the particle size. The same authors testing electrostatic filters with singly charged aerosol observed that the contribution of the electrostatic forces caused by the Coulomb attraction is, instead, significant for the smaller particles, and it loses relevance when the particle size increases.

The results depicted in Figure 4 were achieved with a neutralized aerosol; testing the penetration using neutralized aerosols is meaningful as their charge state is similar to that reached by the atmospheric particles long enough after their production.[18] This aerosol, although neutral as a whole, contains charged particles, and the mean charge on each particle increases with the particle diameter.[4] With reference to the dimensional range analyzed, a neutralized aerosol with

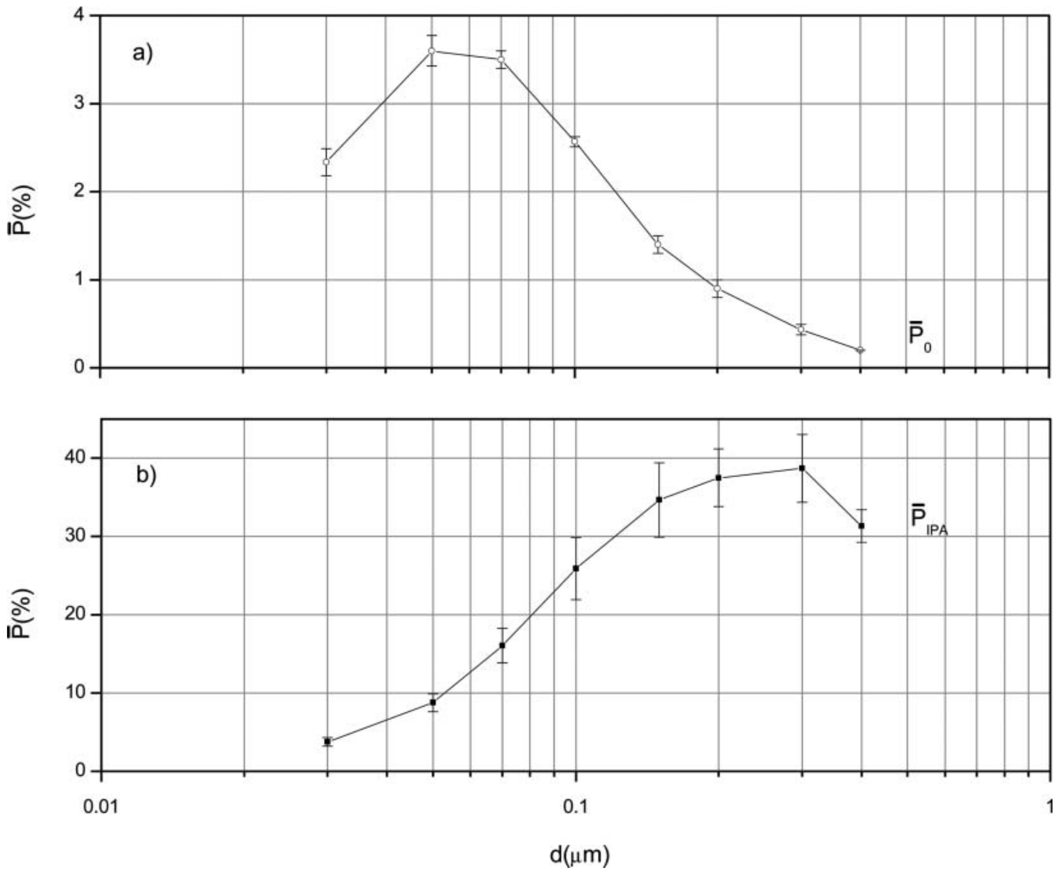

FIGURE 2. Mean penetration of neutralized DEHS aerosol calculated for a) no IPA treated ($\overline{P_0}$) and b) IPA treated ($\overline{P}_{IPA}$) facepieces, without paraffin oil loading. The standard deviation bar is reported for each point.

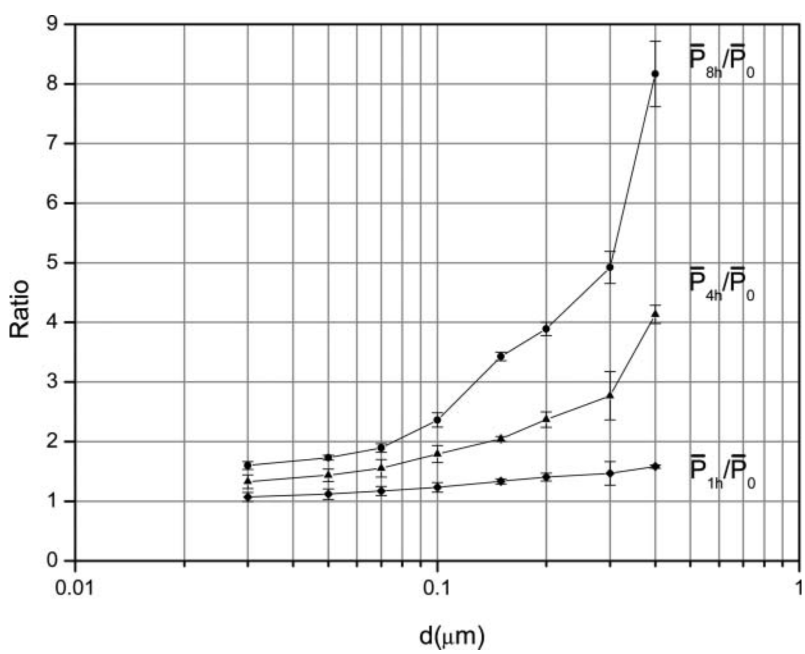

FIGURE 3. Ratio of mean filter penetration ($\overline{P}_t/\overline{P}_0$) after different exposure times to paraffin oil aerosol ($\overline{P}_{1h}, \overline{P}_{4h}$, and $\overline{P}_{8h}$) to the mean initial value ($\overline{P}_0$) for different particle sizes of neutralized DEHS aerosol. The standard deviation bar is reported for each point.

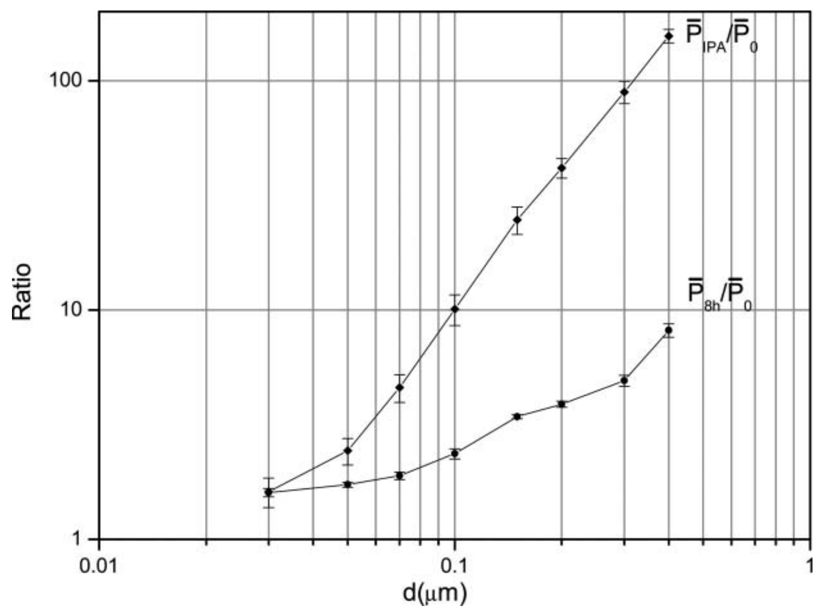

FIGURE 4. Ratio of mean filter penetration treated with IPA ($\overline{P}_{IPA}$) and after 8hr of paraffin oil loading ($\overline{P}_{8h}$) to mean filter penetration without any treatments ($\overline{P}_0$) for different particle sizes of neutralized DEHS aerosol. The standard deviation bar is reported for each point.

particles of 0.03 μm diameter contains 70% neutral particles and has, on average, about 0.4 elementary charge on each particle, while a neutralized aerosol with particles of 0.40 μm diameter contains 20% neutral particles and has, on average, about 1.5 elementary charge on each particle. Therefore, the increasing trend of the two curves shown in Figure 4 is determined by the variation of both Coulomb and polarization forces strictly dependent on the diameter and the electrical charge of neutralized aerosol particles. The polarization forces, as already seen, become more effective by increasing the particle size and act on both neutral and charged particles; the contribution of the Coulombic forces, instead, is more complex to be defined. In fact, the capture efficiency of the Coulombic forces decreases by increasing the aerosol particle size, but at the same time, it is positively affected by the increase of the mean charge on each particle.

CONCLUSION AND RECOMMENDATIONS

This study showed that electrostatic filter capture efficiency is decreased due to loading with a paraffin oil aerosol. Penetration measurements carried out using neutralized monodisperse DEHS aerosols after subsequent paraffin loads showed a gradual penetration increase for all the analyzed aerosol particle sizes and, at the same time, a shift of the most penetrating particle size toward larger diameters.

The penetration increase, expressed as penetration ratio, grows with the diameter of the test aerosol. This behavior can be attributed to the effect of the electrostatic forces that increases with the size of the neutralized aerosol particles in the 0.03–0.40 μm range.

The gradual loss of performance of the filtering facepiece measured during exposure to an oily aerosol flow highlights the need for complying with the manufacturer instructions when it is specified that their use as personal protective equipment in the workplace has to be restricted to a single shift. However, it is also important to keep in mind that the overall particle penetration into a filtering facepiece respirator is usually dominated by the degree of face seal leakage and not by penetration through the filter medium.

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