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Original Article

Evaluation of performance loss of paraffin oil loaded filtering facepieces

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Abstract: Penetration measurements through commercially available filtering facepieces were performed with monodisperse DEHS aerosols ranging from 0.03 μm to 0.40 μm (either singly charged or neutralized), before and after 500 mg of paraffin oil loading. The distinct behavior of Coulomb and polarization capture efficiency is studied: as in the case of non loading also in the case of loading 500 mg of paraffin oil, the electrostatic capture mechanisms are mainly due to the Coulomb contribution up to aerosol particle diameter of about 0.10 μm, just when the polarization contribution becomes substantial. Both Coulomb and polarization capture mechanisms are influenced by the presence of 500 mg of paraffin oil, resulting less effective than the oil unloaded case of about 12% and 11%, respectively. By the occupational hygiene point of view, there is a degradation in the filter performance due to oil loading that the user does not realize because there is no remarkable variation in the breathing resistance.

Key words: Respirators, Electrostatic filters, Penetration, Oil load, Industrial hygiene

Introduction

Filtering facepieces are respiratory protective devices frequently used to reduce inhalation exposure to particulate contaminants. Most filtering facepieces used today are made of electret filtering materials (materials with electrical charges on the fibers)[1]. Referring to these materials, there are mainly two mechanisms of particle removal by electrostatic deposition: one is due to the Coulomb forces, the other is due to polarization forces. The Coulomb forces operate between a charged particle and the opposite sign charges present on the fibers. The polarization forces are due to the electrostatic field around the charged fiber that induces a dipole in a particle, causing it to be attracted toward the fiber. When fibers and aerosol particles are both charged, the electrostatic particle deposition is influenced by a combination of Coulomb and polarization forces[2, 3]. The electrostatic mechanisms, working simultaneously with mechanical mechanisms provide filtering materials with pressure drops lower than those of purely mechanical filtering materials having the same efficiency and superficial area[2]. This feature has encouraged the use of electrostatic materials in respirator filters to decrease breathing resistance and thereby making particle filtering respirators more acceptable to users. However, the efficiency of an electret filter material can be reduced by filtering certain aerosols[4], and the reduction extent depends on the amount of loaded aerosol[5−10] and on the type of loaded aerosols[6−8, 11]. In addition, the effect of the loading was investigated using different particle size of test aerosols[12−15]. The efficiency decrease has been ascribed to: neutralization of the charge on the fiber by opposite charges on the captured aerosol particles[16]; screening of the fiber charge by a layer of captured particles[17]; disruption of the fiber

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charge by the aerosol, either by dissolution of the surface layer or by chemical reaction[8]. Whatever the mechanism, the potential reduction in filtration efficiency is a concern for respiratory protection.

The aim of this work is to show an approach to describe distinctly the behavior of Coulomb and polarization capture efficiency, before and after oil loading, using penetration measurements of aerosols at different state of charge.

Materials and Methods

Facepieces model Mandil FFP2 NR with no exhalation valve, manufacturer D. P. I Sekur, were used to perform penetration measurements. The respirators, meeting the requirement of the European standard EN 149:2001+A1:2009[18], are classified as single shift use only.

Two different aerosols were employed: a loading polydisperse aerosol made of paraffin oil (WOP 40 PB, Merkur) and monodisperse test aerosols of bis(2-ethylhexyl)sebacate (DEHS) with different charge state (neutralized and singly charged).

An aerosol generator (AGW/BM VI–Lorenz Messgeratebau) and an aerosolphotometer (AP2E–Lorenz Messgeratebau) were used to load the filtering facepieces with paraffin oil. The characteristics of the polydisperse paraffin oil aerosol with the corresponding used loading conditions were already reported[12] and they conform to the European Standard EN 13274-7:2008[19].

DEHS neutralized monodisperse aerosol penetration was measured by a Fractional efficiency filter tester TSI 3160, as described in detail elsewhere[12]. To measure DEHS singly charged monodisperse aerosol penetration, the aerosol flow was deviated from the exit of the differential mobility analyzer by a manual 2-way valve, without passing through the exit-neutralizer[20]. The selected monodisperse particles were in the diameter range 0.03–0.40 μm and the testing flow rate was set at 95 ± 1 l/min according to penetration determination procedures reported in the pertinent european standard[19]. 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 level. At the same time of penetration measurements, pressure drop (ΔP) measurements i.e. resistance to the air flowing through the filter[21], were performed by the differential manometer in the TSI 3160. Preliminary penetration tests performed using neutralized and singly charged DEHS aerosols, confirmed the electrostatic type[22] of the studied facepieces.

Each instrument (TSI 3160 and Lorentz system) was equipped with its own filter holder especially structured to contain filtering facepieces: the perimeter of the facepiece was glued around a shaped hole on a plate. The plate was inserted in TSI or Lorenz filter holder making the systems leak tight.

The experiment was performed using isopropyl alcohol (IPA) treated facepieces and IPA untreated facepieces. An IPA-treated facepiece was a filtering facepiece dipped in IPA for 60 minutes and then allowed to air dry for 24 hours. The IPA treatment is regarded as particularly effective in removing most of the electrostatic charges from the fibers and it allowed to study the performance of the filter due to primarily mechanical filtration mechanisms[1, 9, 23–25]. Firstly, neutralized and singly charged DEHS penetration was measured through the IPA treated and the untreated facepieces. Subsequently, an amount of 500 mg of paraffin oil was loaded in the above-mentioned facepieces and neutralized and singly charged DEHS aerosol penetration was measured again. The amount of 500 mg is greater than that a filtering facepiece could load in common working environments[26–29] during a 8-hour shift: environmental surveys carried out in workplaces polluted by oily aerosols refer average concentrations in the range 0.07–4 mg/m^3 with the exception of the value 10 mg/m^3 measured without effective ventilation sistems[29]. Assuming the flow of inhaled air of 38.5 l/min, mean ventilation value as reported for work activity from mild to exhaustive workloads[30], a loaded amount in the range 1.3–185 mg during a 8-hour shift, can be calculated. Nevertheless, for the purpose of this study, an amount of 500 mg of paraffin oil was used to be able to highlight the different behavior of paraffin oil loaded facepieces compared to the unloaded ones. In addition, applying the above described experimental conditions, about 500 mg is the maximum amount of paraffin oil that can be loaded in the IPA treated facepieces (penetration value around 40% as measured by Lorentz system) in our working day. The loading of the same amount of paraffin oil took about four hours in the IPA untreated facepieces.

The experiment was performed three times using each time a couple of facepieces, one IPA treated and the other IPA untreated. In this work only one of the three trials is reported in details; the other two confirmed the reported trend. Two more facepieces, used as controls, were integrated in the experiment to assess the possible effect on the penetration of the airflow used during the paraffin oil loading on the both experimental conditions.

Finally, it is explicitly shown, Table 1, the notation used

Table 1. Notation used for the penetration measurements through filtering facepieces to indicate the amount of oil loaded, the IPA-treatment and the test aerosol charge state

Penetration notation	Paraffin oil load (mg)	IPA treatment	Aerosol charge	ΔP^{A} (Pa)
N_0	0	No	Neutralized	139
S_0	0	No	Singly charged	139
N_0^{IPA}	0	Yes	Neutralized	139
S_0^{IPA}	0	Yes	Singly charged	137
N_{500}	500	No	Neutralized	142
S_{500}	500	No	Singly charged	141
N_{500}^{IPA}	500	Yes	Neutralized	141
S_{500}^{IPA}	500	Yes	Singly charged	142

^{A} Pressure drop measured at a flow rate of 95 l/min

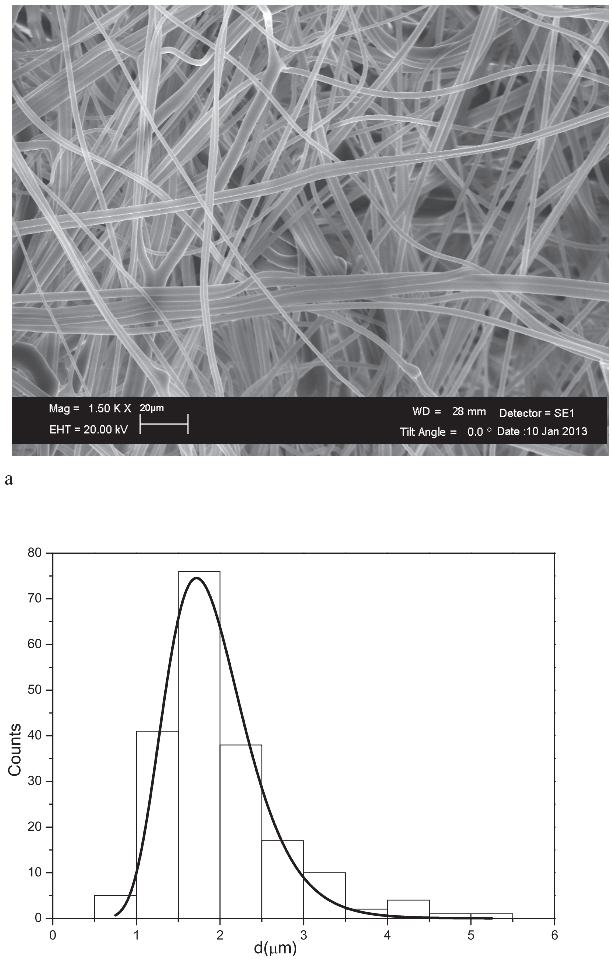

Fig. 1. a) SEM Image of filtering material; b) Histogram of fiber filter diameters and the corresponding fit (solid line) with the log-normal distribution.

to identify the penetration measurements: the test aerosol charge state is indicated by N for neutralized aerosol and S for singly charged aerosol; the amount (mg) of oil loaded in the facepiece is indicated as 0 or 500 in the subscript index; the IPA-treatment is indicated as IPA in the superscript index.

Results and Discussion

Macroscopically the filtering facepiece is made of three parts: the support shell outside, the support shell inside and the electret filter in the middle.

The electret filter thickness (t) and the packing density (α) are respectively $t=(636\pm9)$ μm and $\alpha=(0.031\pm0.002)$ according to the information provided by manufacturer. The fiber diameter of the electret filter was determined by analyzing the images obtained by the scanning electron microscope (SEM, Leo S440). As it is shown in Fig. 1a, the electret filter was composed of fibers with various diameters (polydisperse fibrous filter). The fiber diameter distribution (200 fibers) was found to follow the log-normal distribution[3)], solid line in Fig. 1b, with the geometric mean fiber diameter $d_{Fg}=1.8$ μm and the geometric standard deviation, $\sigma_{gdF}=0.3$ μm.

The filter physical characteristics (d_{Fg}, t, α) and consequently the mechanical efficiency were assumed the same in the entire experiment. Especially it was verified that the pressure drop values obtained during the TSI penetration measurements at flow rate of 95 l/min do not remarkably change in the case of oil loading and /or IPA treated as reported in the last column of Table 1.

Typical penetration measurements of neutralized and singly charged aerosols through an IPA treated and an IPA untreated facepiece are shown in Fig. 2 in the case of 0 mg of paraffin oil loaded. Firstly, for the next considerations about electrostatic capture mechanisms, it is worth to be stressed that even if the neutralized aerosol can be considered neutral as a whole, the net charge on each particle cannot be negligible. As already reported[12)] a neutralized aerosol with 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. To sum up, the smaller the neutralized aerosol particle diameter the better the assumption of neutralized as neutral aerosol in the study of electrostatic capture mechanism.

In Fig. 2, comparing curve S_0 with curve N_0^{IPA}, it is evident that the effect of electrostatic capture mechanisms on the performance of electret filters is very substantial.

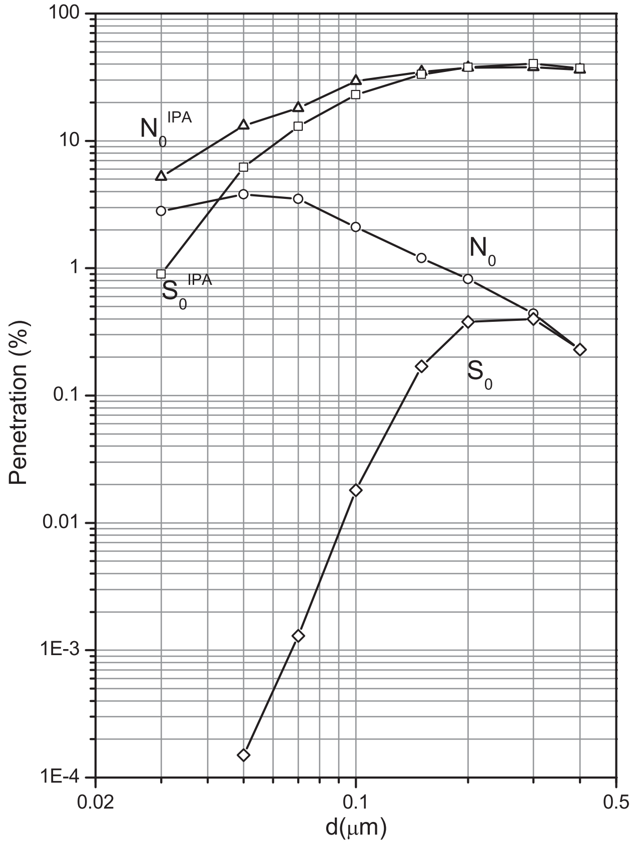

Fig. 2. Neutralized and singly charged DEHS aerosol penetration curves at 0 mg of oil paraffin load (unloaded case) through an untreated (N_0, S_0) and through an IPA-treated (N_0^{IPA}, S_0^{IPA}) facepiece.

Curves S_0 and N_0 converge at the larger particle-size range because the Coulombic capture becomes negligible for large particles. The most penetrating particle size of the electret filter is a function of the charge state of the aerosol, being close to 0.30 μm for singly charged particles and close to 0.05 μm for neutralized particles. This is because the Coulombic effect increases with decreasing particle size and the polarization effect increases with increasing particle size[2]. Coulomb capture mechanism is attenuated of four order of magnitude by IPA treatment, comparison between S_0 and S_0^{IPA} curves at small particle diameter, while polarization capture mechanism of two orders, comparison between N_0 and N_0^{IPA} curves at large particle size.

The above observations agree qualitatively with theoretical predictions of electrostatic capture mechanisms[2], and they are also valid when loading 500 mg of paraffin oil. In this case, the penetration curves are shown in each panel of Fig. 3 where they are put in comparison with the corresponding curves of the unloaded case. In details, Fig. 3a, is related to penetration of singly charged aerosol, comparison between S_0 and S_{500} curves, and Fig. 3b to penetration of the neutralized aerosol, comparison between N_0 and N_{500} curves. N_{500} and S_{500} curves have the same trend of the unloaded case; it is also noteworthy an increase in the penetration value on the entire aerosol particle size range. In Fig. 3c and 3d are shown the similar penetration curves of singly charged and neutralized aerosols in the case of IPA-treated facepiece. At the smallest aerosol particle sizes, the specific role of test aerosol charge state is still marked: N_0^{IPA} penetration value is higher than that of S_0^{IPA} and this behavior could be due to Coulomb interaction between the aerosol charge and the residual charges on the fibers after IPA treatment. The same effect can be appreciate in the case of 500 mg of paraffin oil loading although the penetration values are just little higher. It is worth stressing that penetration measurement at 0.03 μm with singly charged aerosol (S_0 and S_{500}), was not considered due to low filter penetration (less than 10^{-5}%). Standard deviation bars, derived from the 95% confidence intervals of the measurements, are not appreciable in the graphs with the adopted scale.

In what follows, the experimental penetration curves will be used to obtain the contributions (Coulomb and polarization) to the electrostatic filter efficiency when 0 mg and 500 mg of paraffin oil were loaded.

When testing an IPA-treated filter with neutralized aerosol, the measured penetration (N_0^{IPA}) can be considered mainly due to the mechanical capture mechanisms[1, 9, 23–25], and it can be explicitly written as[21]:

$$N_0^{IPA} = \exp(-k(E_{mech})) \tag{4}$$

Where E_{mech} is the mechanical efficiency and k is:

$$k = \frac{4\alpha t}{\pi d_{Fg}} \tag{5}$$

α is the packing density, t is the filter thickness, and d_{Fg} is the geometric mean fiber diameter.

When testing an electret filter with neutralized particles, the measured penetration (N_0) involves mechanical and polarization capture mechanisms[2] and, in a first approximation, it can be written as:

$$N_0 = \exp(-k(1-(1-E_{mech})(1-E_{pol0}))) \tag{6}$$

The polarization efficiency at 0 mg of paraffin oil loaded, E_{pol0}, was obtained by means of the ratio between N_0 (6) and N_0^{IPA} (4) and it is explicitly given by:

$$E_{pol0} = \ln\left(\frac{N_0^{IPA}}{N_0}\right)\frac{1}{k(1-E_{mech})} \tag{7}$$

When testing an electret filter with singly charged par-

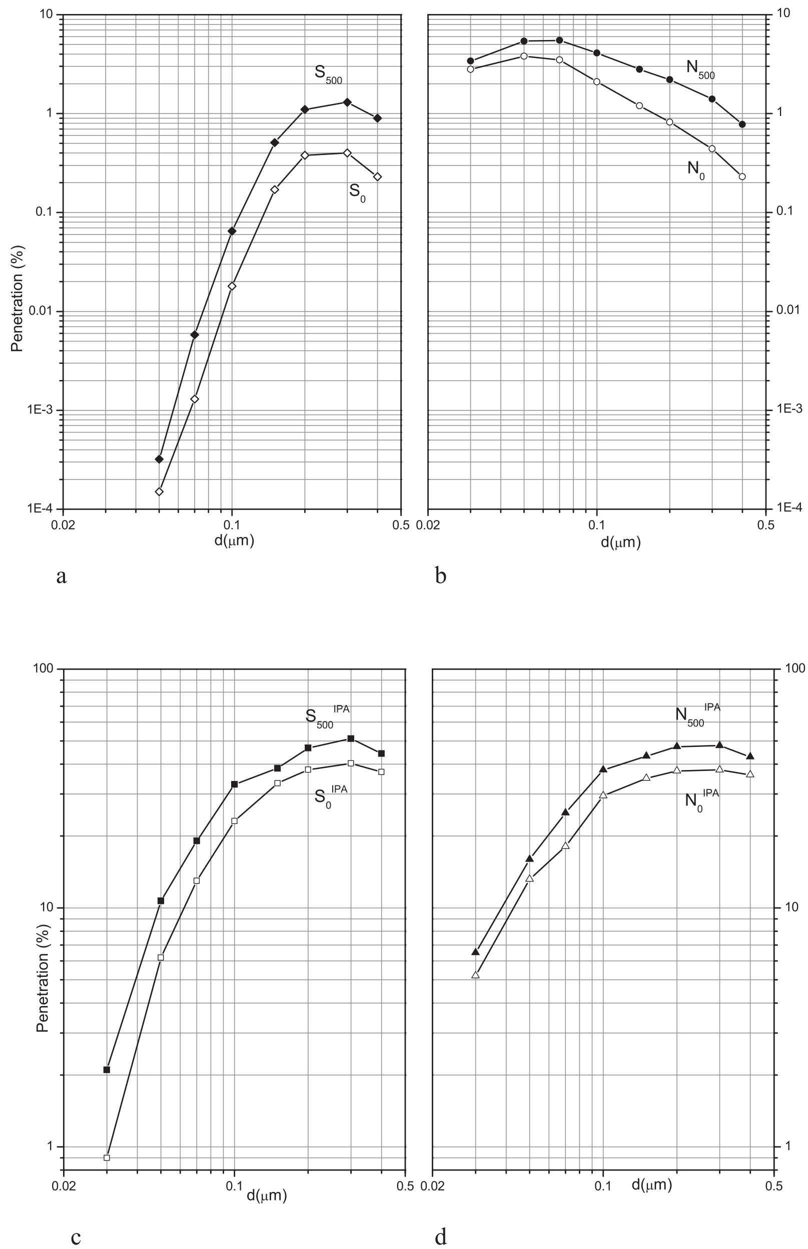

Fig. 3. Comparison between penetration curves at 0 mg and 500 mg of paraffin oil load through an untreated facepiece with singly charged (a) and neutralized aerosol (b) and through an IPA treated facepiece with singly charged (c) and neutralized aerosol (d).

ticles, the measured penetration (S_0) involves three capture mechanisms[2)]: mechanical, Coulomb and polarization and it can be written as:

$$S_0 = \exp(-k(1-(1-E_{mech})(1-E_{pol0})(1-E_{Cou0}))) \tag{8}$$

The Coulomb efficiency at 0 mg of paraffin oil loaded, E_{Cou0} was obtained by means of the ratio between S_0 (8) and N_0 (6) and it is explicitly given by:

$$E_{Cou0} = \ln\left(\frac{N_0}{S_0}\right)\frac{1}{k(1-E_{mech})(1-E_{pol0})} \tag{9}$$

The polarization and the Coulomb efficiency at 500 mg of paraffin oil loaded, E_{pol500} E_{Cou500}, were obtained in analogy with (7) and (9).

The above calculated efficiencies are plotted in Fig. 4. As expected, in the case of loading 0 mg of paraffin oil also in the case of loading 500 mg of paraffin oil, the electrostatic capture mechanisms are mainly due to the Coulomb contribution up to about 0.1 μm, just when the polarization contribution becomes substantial. In our experimental conditions the mean ratio between E_{Cou0} and E_{Cou500} for d

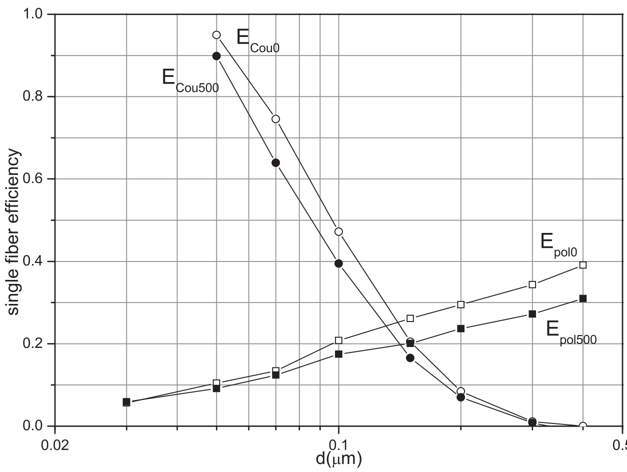

Fig. 4. Coulomb and polarization efficiency obtained at 0 mg (E_{Cou0} and E_{pol0}) and at 500 mg of oil paraffin load (E_{Cou500} and E_{pol500}).

<0.15 μm is 1.14 ± 0.07 while the mean ratio between E_{pol0} and E_{pol500} for $d>0.15$ μm is 1.120 ± 0.004. These results highlight that both Coulomb and polarization efficiency are attenuated by loading 500 mg of paraffin oil of about 12% and 11%, respectively.

Conclusion

This study presents a way to show the behavior of Coulomb and polarization electrostatic capture mechanism of filtering facepieces, before and after oil loading. The presence of paraffin oil leads to the attenuation of both the components of electrostatic efficiency.

By the occupational hygiene point of view, even if the amount of oil is greater than the amount of oil that can be loaded in the filtering facepieces in working environments during a workshift, the filtering facepieces efficiency reduction indicates a degradation in the filter performance that the user does not realize because there is no remarkable variation in the breathing resistance, as evidenced in the pressure drop measurements.

The loss of performance of the studied filtering facepieces due to oil loading indicates the need of complying with the manufacturer information that limits their use to a single shift.

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