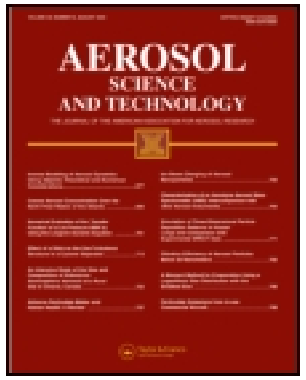

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Particle Reentrainment from Fibrous Filters

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ABSTRACT. When a respirator wearer breathes normally, airborne bacteria and particles may be collected by the filter medium of the respirator. If these particles are reentrained again by sneezing or by coughing during the exhalation cycle, they may reach other targets. To study this hypothesis, particle reentrainment from polymer and glass fiber filters was investigated by measuring the number of reentrained particles when loaded filters were subjected to air velocities higher than typical filtration velocities in the direction opposite to the filtration flow. The filters were loaded with mono- or polydisperse solid particles or liquid droplets. Particle loading and reentrainment were quantified by a real-time aerosol size spectrometer. The maximum reentrainment air velocity used in the tests was 500 cm/s, almost one hundred times the 6.6 cm/s filtration velocity during particle loading. The latter is typical for inhalation through a half-mask respirator at medium work load. For the test conditions, the reentrainment of 0.6–5.1 μm particles increases approximately with the square of particle size and the reentrainment velocity, and decreases with increasing relative humidity. The rise time in reaching the reentrainment air velocity has negligible influence on the degree of reentrainment. Particle and filter type were found to significantly affect particle reentrainment. The minimum reentrainment velocity decreases with increasing particle size. Electrical charges on the filter fibers significantly increase the collection of submicrometer particles, but their reentrainment is only slightly impeded by the embedded charges. The number of reaerosolized particles decreased slightly with filter thickness, which indicates that most of the reaerosolized particles are reentrained from the front layer of the filter. AEROSOL SCIENCE AND TECHNOLOGY 27:394–404 (1997) **© 1997 American Association for Aerosol Research**

INTRODUCTION

This study on the reentrainment of particles from fibrous filters was motivated by concern about the inhalation of tuberculosis bacteria in healthcare and other environments where *Mycobacterium tuberculosis* may be present as airborne particles. The bacteria and other particles may reach the human respiratory tract by penetrating through the filter medium of the respirator (Willeke et al., 1996) or through a face-seal leak, if one or more leak sites are present between respirator and face (Han et al.,

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1997). The aim of this study was to determine the conditions under which particles collected on a fibrous filter may be reentrained from the filter fibers. The hypothesis is that the respirator wearer may inhale reaerosolized particles, if he or she inhales suddenly at a higher flow rate. If the respirator wearer sneezes or coughs, bacteria may be reentrained in the direction opposite to inhalation, i.e., they may become present again in the air environment, from where they may reach other targets. If the respirator wearer sneexes or coughs after having left the controlled environment, the reentrained bacteria may reach the respiratory tract of unprotected people. Since the appearance of multidrug resistant tuberculosis bacteria with high pathogenicity (Bloom and Murray, 1992), the presence of tuberculosis bacteria in the air, even at extremely low concentrations, has become of considerable concern in the health-care industry.

The reentrainment of particles from surfaces was studied for simple attachment geometries (Cleaver and Yates, 1973; Zimon, 1982; Wen and Kasper, 1989; Masuda et al., 1994). Particle detachment will occur only when an external force, e.g., air drag, overcomes the adhesion force between a particle and the surface to which it is attached. Corn (1966) and Zimon (1982) have identified the following types of adhesion force: the van der Waals force due to molecular interaction between the particle and the surface; electrostatic attraction, which exists if an electric charge is present on either the particle or the surface, or if charges are simultaneously present on the particle and the surface, but have opposite polarity; surface tension caused by water molecule deposition between the particle and the surface when the relative humidity is sufficiently high. The flow field around a nonspherical particle attached to a curved surface is complex (Zimon, 1982; Mullins et al., 1992). Thus, most of the published reentrainment studies have focused on particles attached to an ideal surface such as a flat plate or the inner surface of a tube. Theoretical models, such as the "burst theory" by Cleaver and Yates (1973) and the "kinetic particle desorption model" by Wen and Kasper (1989) are based on ideal conditions and are not directly applicable to more complex cases, such as particle reentrainment from filter fibers.

Very limited information is available on particle reentrainment from a fibrous filter (Larsen, 1958; Corn and Silverman, 1961). Since no advanced aerosol instrumentation was available at the time of these earlier studies, the reentrainment mechanism from fibrous filters was analyzed by measuring the change in pressure drop across the test filters, or observing the retained particles by microscopy. While a measured decrease in pressure drop across a test filter indicates particle reentrainment from the filter, this method does not enable the researcher to record the number of particles reentrained. Also, pressure drop is not a good indicator of reentrainment, if the filter is overloaded. When analyzing reentrainment by microscopic observation of the retained particles on a single fiber after exposure to an air jet, the flow around the test fiber may not be representative of the complex flow through the filter medium. The limited results from these earlier studies indicate that reentrainment will occur only at air velocities through the filter that are at least 10 times higher than normal filtration velocities.

When coughing or sneezing through a respirator, all of the exhaled air flow is directed toward the respirator filter area in a very short time period, which results in an air velocity through the filter medium that is much higher and in the opposite direction to the air flow during normal breathing. Thus, one may expect particle reentrainment to occur during sneezing or coughing. In this study, the amount of particles reentrainment from fibrous filters was measured by dynamic particle size spectrometry over a range of particle sizes and flow conditions.

EXPERIMENTAL METHODS AND MATERIALS

Filter Loading

Before performing reentrainment experiments, the filter samples were loaded with test particles, as schematically shown in Fig. 1. Polystyrene latex (PSL) and dissolvable test particles were generated by a three-nozzle Collison nebulizer (BGI, Inc., Waltham, MA) while air cleaner dust was dispersed by a fluidized bed generator (model 3400, TSI, Inc., St. Paul, MN). In the test setup, filtered room-temperature air is mixed with the aerosol flow to dilute the particle concentration to a desired level. The diluted aerosol flow passes through a 10 mCi ^{85}Kr electrical charge neutralizer (TSI, Inc., St. Paul, MN) to reduce the charge level to Boltzmann equilibrium, and then enters a loading chamber (12 cm in diameter) with the filter sample facing the aerosol flow.

The filter sample is held in a 40 mm open-face filter holder (Gelman Sciences, Ann Arbor, MI). An air flow rate of 5 l/min is passed through the filter sample. This results in a filtration velocity of about 6.6 cm/s which simulates the average air velocity through a half-mask respirator filter during inhalation at medium work load. An "Aerosizer" real-time aerosol size spectrometer (Amherst Process Instruments, Inc., Hadley, MA) was used to measure the aerosol concentrations up- and downstream of the filter sample. The aerosizer used in these experiments detects particles down to about 0.2 μm and adequately measures aerosol concentrations down to about 0.5 μm, thus making it possible to perform reentrainment experiments in the sub- and super-micrometer size range (Cheng et al., 1993; Qian et al., 1995). The instrument's counting efficiency decreases from about 100% at 0.5 μm to 0% at 0.2 μm. Each filter sample of about 12 cm^2 was loaded with about 1.2×10^6 particles. This load was the same for each tested particle size, which resulted in a particle surface density on each filter of about 10^5 particles/cm^2. The filter load was calculated by measuring the volumetric air flow rate through the filter sample during loading, Q_L, the loading time, t_L, the upstream aerosol concentration, C_{up}, and the downstream aerosol concentration, C_{down}. The latter two yield the filter collection efficiency, E,

$$E = 1 - \frac{C_{\text{up}}}{C_{\text{down}}} \tag{1}$$

$$\text{filter load} = C_{\text{up}} Q_L E t_L. \tag{2}$$

The filter collection efficiency of the polypropylene filter tested in this study ranged from about 93% for 0.6 μm particles to 99.8% for 5.1 μm particles. All experiments were performed at 25°C, cor-

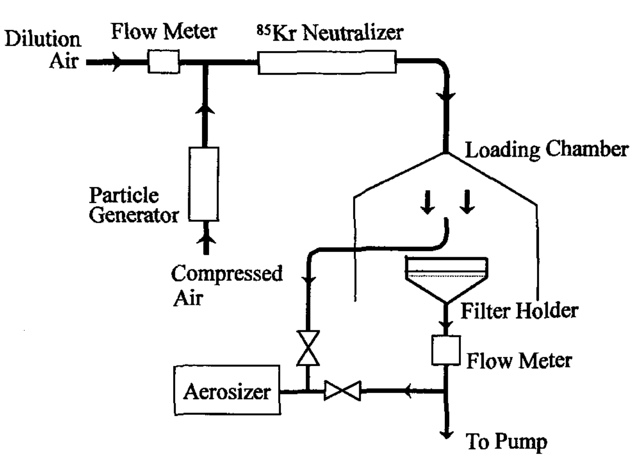

FIGURE 1. Experimental setup for filter sample loading.

responding to the controlled temperature of the building and its air supply. To avoid potential deposition of room dust on the filter sample, the loading setup was placed in a particle-free hood.

Reentrainment

The loaded filter was moved to the particle reentrainment system shown in Fig. 2. A needle valve controls the flow rate through the filter sample and a quick-release valve establishes the flow. The relative humidity of the air flow was about 20% for all experiments, except where indicated. A mass flow meter (model 500-8, Kurz Instrument, Inc., Carmel Valley, CA) connected to an oscilloscope (7623A, Tektronix, Inc., Beaverton, OR) measures the time it takes to establish the reentrainment flow after the quick-release valve is opened. In the experiments for which data are presented, the flow reached its average value after about 0.3 s, but oscillated about it for about 1.8 s.

The relative humidity of the reentrainment air flow can be increased by bubbling part of the flow through a vertical column filled with water and Raschig rings, as shown in Fig. 2. The reentrainment velocity is increased by decreasing the open filter area while keeping the flow rate the same. This is achieved by placing the entire filter sample between two plates with concentric holes that correspond to a specific reentrainment velocity. The filter sample is sealed against the plates with "O" rings.

A photometer (model RAM-S, MIE, Inc., Bedford, MA) samples from downstream of the filter sample in parallel with the Aerosizer using the same inlet. The Aerosizer records the number of reentrained particles, while the photometer monitors the time change in reentrained particle concentration. The short burst of reentrained particles is recorded by the oscilloscope. The relative humidity of the reentrainment flow is monitored by a thermohygrometer downstream of the filter holder (model DHTD, Fisher Scientific, Pittsburgh, PA). The reentrainment experiments were also performed at 25°C in a particle-free hood. The degree of particle reentrainment, R, is expressed as the ratio of reentrained to loaded particles,

$$R = \frac{\text{number of reentrained particles}}{\text{number of loaded particles}} \times 100\%. \tag{3}$$

Due to the relatively large variations in particle reentrainment percentages, each experimental condition was repeated at least six times.

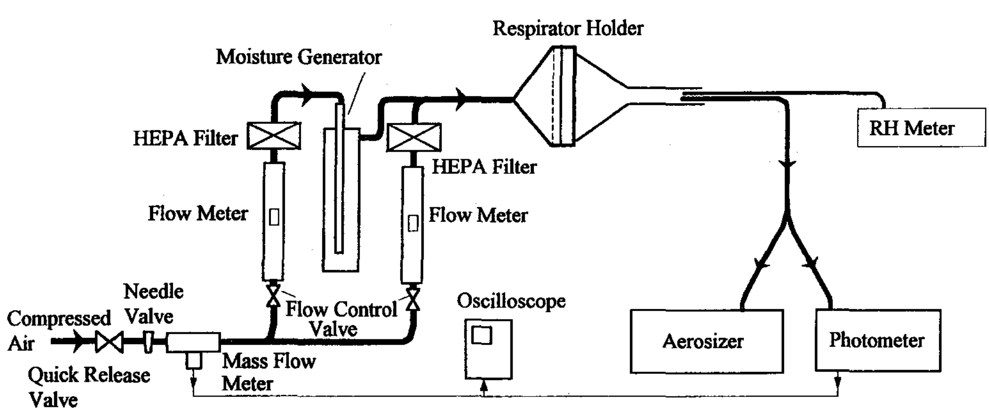

FIGURE 2. Experimental setup for particle reentrainment measurement from fibrous filter samples.

Materials

Three types of fibrous filter used in respirators were tested in this study: (1) a glass-fiber high efficiency particulate air (HEPA) filter removed from a respirator cartridge (Willson Safety Products, Reading, PA), 0.8 mm thick, fiber diameter = 0.1–5 μm, solidity ≈ 12%; (2) a polypropylene filter from a half-mask respirator (3M, St. Paul, MN), 1.1 mm thick consisting of two layers, fiber diameter = 5–10 μm, solidity ≤ 10%; and (3) a polypropylene/modacrylic felt filter from a half-mask respirator (Technol Medical Products, Inc., Fort Worth, TX), 2.5 mm thick, fiber diameter ≈ 20 μm, solidity ≈ 5%. All of these filters had electrical charges imbedded in them during their manufacture. (Almost all fibrous filter media used in respirators have electrical charges imbedded in or attached to the fibers for maximum particle collection efficiency at the least pressure drop across the respirator.) While respirator filters are expected to maintain most of their electrical charges during normal wear, several experiments were also performed with discharged filters. The experiments with discharged filters do not reflect actual use conditions, but were performed to help in the interpretation of the reentrainment process. The filters were electrically discharged by immersing them in isopropanol for 1 h and then drying them in still air for over 24 h (Chen et al., 1993).

Since adhesion and detachment of particles are known to depend on particle material and size (Hinds, 1982; Baron and Willeke, 1993), experiments were conducted with four different types of particles: monodisperse polystyrene latex (PSL, Bangs Laboratory, Inc., IN), sodium chloride (NaCl, Fisher Scientific, Pittsburgh, PA), corn oil (Eastman Kodak Co., Rochester, NY) and air cleaner dust (fine dust collected in an electrostatic precipitator). Experiments with monodisperse PSL particles were performed at five different particle sizes: 0.60, 1.02, 1.94, 2.96, and 5.10 μm.

EXPERIMENTAL RESULTS AND DISCUSSION

The first question addressed was whether the rise time of the reentrainment flow had any effect on the degree of particle reentrainment. For a final reentrainment velocity of 500 cm/s, the rise time was varied from 0.1 ms to 10 s in tests with polypropylene filters loaded with PSL particles of all five test sizes. Different rise times were achieved by varying the speed of manually opening a valve. The air flow was recorded by a mass flow meter connected to an oscilloscope. The data recorded by the photometer and the Aerosizer indicated that the percentage of reentrained particles from the fibrous filters was approximately the same, no matter how quickly the valve was opened to reach the final reentrainment air velocity. Thus, we conclude that, for a given fibrous filter loaded with particles, the degree of reentrainment is solely a function of air velocity through the filter medium. Several additional tests were performed in which an approximately 300 ms pulse of air was passed through the filter medium, followed by two additional pulses of the same magnitude. No measurable amount of particle reentrainment was found to result from the two additional pulses. We conclude from this that a particle is immediately reentrained when the drag force by the air flow over the particle exceeds the particle's force of adhesion to the filter fiber.

Figure 3a shows that the degree of reentrainment is significant at a reentrainment air velocity of 500 cm/s opposite to the loading direction, when the filter has been loaded at a filtration velocity of 6.6 cm/s. This reentrainment velocity is about 70 times the filtration velocity and exceeds violent sneezing or coughing during exhalation. We have estimated that a person can exhale a maximum tidal lung volume of 2 l in about 0.3 s during sneezing or coughing. For a mouth area of 22 cm^2, that results in an exhalation velocity and therefore reentrainment velocity of 300 cm/s. As seen in Fig. 3a, the percentage of reentrained particles increases approximately with the square of particle diameter, d_p, for a

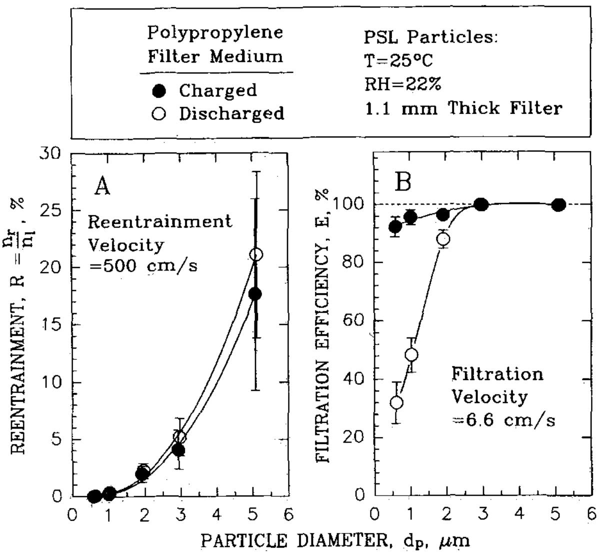

FIGURE 3. Effect of particle size on (a) particle reentrainment, (b) filtration efficiency.

polypropylene filter in its normally charged state as well as in the artificially discharged state. The PSL particle reentrainment from the charged filter is about 0.3% at 1 μm and increases to 17% at 5.1 μm. As indicated by Corn (1966) and Zimon (1982), the adhesion force increases approximately linearly with particle size while the air drag force increases with the square of particle size. Therefore, the air drag force increases faster with particle size than the adhesion force resulting in the observed relationship between particle reentrainment and particle size at the given test conditions.

The degree of particle reentrainment was found to be slightly higher for particles attached to discharged polypropylene filters, Fig. 3a, although their filtration efficiency is considerably lower in the near- and submicrometer size range, Fig. 3b. The difference in particle reentrainment may be insignificant, since the two curves are within each other's range of measurement variability. The similarity of the curves in Fig. 3a, but the difference in Fig. 3b may be interpreted as the following: electrically charged filters attract particles to their surfaces; thus, the eleckical force of attraction is the principal force for particle removal in the submicrometer particle size range for these test conditions. Once the particles no longer move through the air, but are attached to the filters, some of the previously mentioned adhesion forces other than the electrostatic force of attraction appear to dominate.

If particles can be reentrained from discharged filters somewhat more easily than from charged filters, the minimum reentrainment velocity is expected to be lower. This is seen in Fig. 4: the minimum reentrainment velocity is somewhat lower for the discharged polypropylene filter. The minimum reentrainment velocities for PSL particles attached to polypropylene filters is 194 cm/s for 0.6 μm particles, 130 cm/s for 1.02 μm particles and about 113 cm/s for 2.96 pLm and larger particles. We define the minimum reentrainment velocity as the air velocity at which reentrained particles are detected by the Aerosizer (Fig. 2). Since the aerosizer samples from the reentrained particle flow, the data should not be overinterpreted when only a few particles are reentrained. The significance of the adhesion force increases with decrease in particle size, thus necessitating a higher reentrainment air velocity.

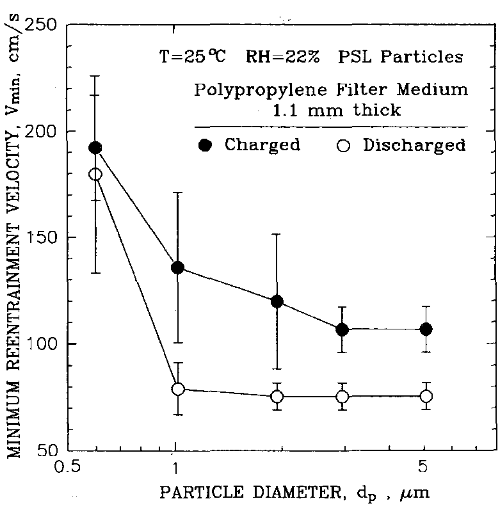

FIGURE 4. Effect of particle size on the minimum reentrainment velocity from polypropylene filters. The reentrainment flow direction is opposite to the filter loading direction.

Figure 5 shows that at these test conditions the percentage of reentrained particles depends approximately on the square of the reentrainment air velocity. The effect on particle size is again significant. The percentage of reentrained particles is again somewhat higher for the discharged filter; however, this difference may not be significant, as pointed out before.

In order to gain additional understanding of the reentrainment process, experiments were performed with polypropylene filters of different thickness, L, while all other properties were the same. Figure 6a shows that the percentage of particles reentrained from a charged polypropylene filter is essentially independent of filter thickness. This independence is expected, if most of the particles collected during the loading cycle are deposited on the uppermost fibers of the filter. A similar behavior is observed for discharged filters, Fig. 6b. When the direction of reentrainment is reversed, i.e., the reentrainment direction is the same as the loading direction, the percentage of reentrained particles decreases with filter thickness, Fig. 6c and d. In this scenario, a similar percentage of particles is reentrained, but a percentage of that fraction is filtered out again, as the particles move through the filter. For tests with bouncy PSL particles at a high filtration velocity of 500 cm/s, the percentage of reentrained particles decreases by one to 1 and $1\frac{1}{2}$ decades for the test particle sizes, as the filter thickness is tripled. For a discharged filter, a greater amount of particles remains

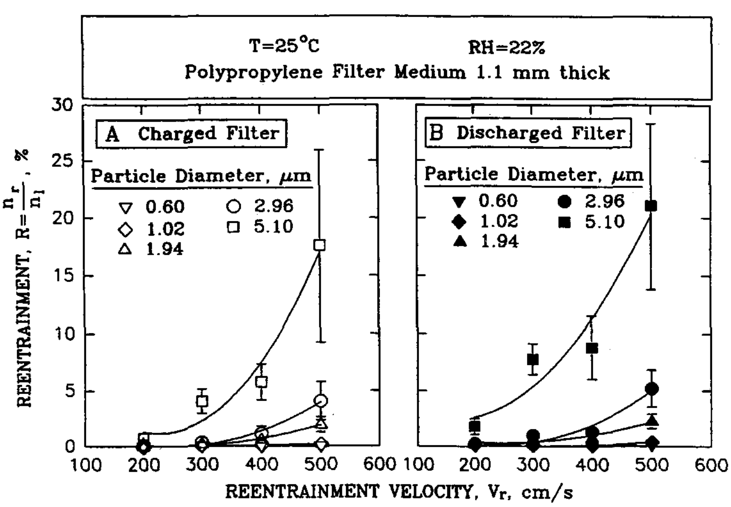

FIGURE 5. Particle reentrainment from polypropylene filters at different reentrainment velocities.

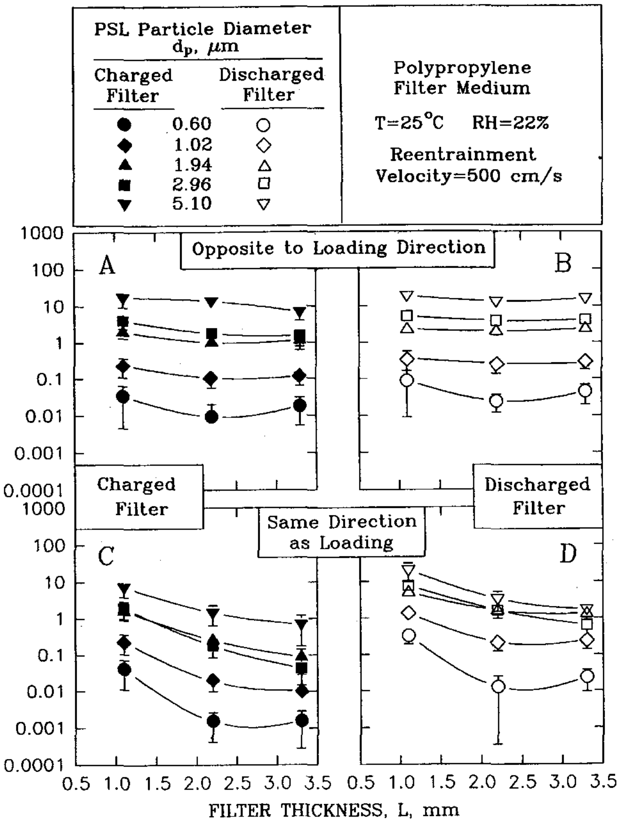

FIGURE 6. Particle reentrainment from filters of different thickness. (a) and (b) are for reentrainment opposite to the direction of filter loading; (c) and (d) are for reentrainment in the same direction as the filter loading.

reentrained, as less of the reentrained particles are collected by the filter, Fig. 6d vs 6c.

Figure 7 shows the effect of filter type on particle reentrainment. Each of the tested filters is made of different materials and represents different fiber sizes and solidities, as described in the Materials section. Thus, it is reasonable to expect differences in the reentrainment percentages. As seen in Fig. 7, the lowest PSL particle reentrainment, ca. 0.01 %, is from charged felt, made from a mixture of polypropylene and modacrylic. There is no significant reentrainment difference between the glass fiber HEPA and the polypropylene filters in the particle size range from 0.6 to 3.0 μm. For particles above 3.0 μm, however, the reentrainment appears to be higher for the polypropylene filters. This difference, if significant, cannot be explained without extensive further testing of these filters and more exact knowledge of the filter characteristics of these materials.

Particle adhesion depends on the material properties of the particles and fibers and the geometry of the contact areas between the particles and the filter samples. While Fig. 7 shows a strong effect of the filter characteristics, Fig. 8 shows that the particle characteristics also have a strong effect on reentrainment. As seen in Fig. 8, corn oil particles are not reentrained at all, while air cleaner dust is reentrained the most. Liquid corn oil droplets are known to form a beadlike structure around the filter fibers (Brown, 1993) which makes them difficult to blow off. Air cleaner dust consists of solid irregularly shaped particles. Agglomeration of two or more dust parti-

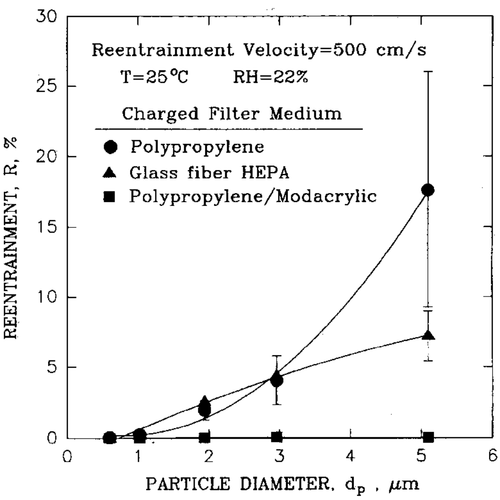

FIGURE 7. PSL particle reentrainment from three filter media. The reentrainment direction is opposite to the filter loading direction.

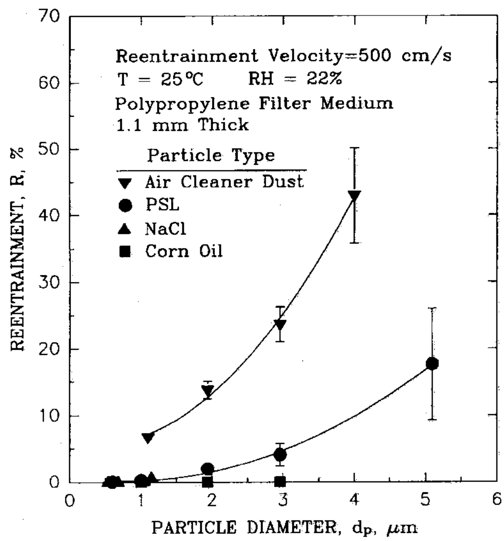

FIGURE 8. Reentrainment of four types of particles from electrically charged polypropylene filters. The reentrainment flow direction is opposite to the filter loading direction.

cles, which we observed by microscopy, results in a smaller contact area per unit mass of particle than for a single particle (Mullins, 1992). Furthermore, the air drag force is larger on irregularly shaped and agglomerated particles, making it easier for them to be reentrained. Thus, reentrainment is a high 42% for 4 μm air cleaner dust deposited on polypropylene filters when subjected to a reentrainment air velocity of 500 cm/s. The reentrainment of spherical PSL particles is lower: 10% for 4 μm particles. Our NaCl data represent only small particles, as their dispersion from a liquid solution in a Collison nebulizer results primarily in submicrometer-size particles. The NaCl particle reentrainment is about the same small percentage ($\sim 0\%$) as that of the PSL particles in the small-particle size range.

Figure 9 shows the effect of relative humidity on particle reentrainment from polypropylene filters. In order to avoid water adsorption by the particles, only hydrophobic PSL particles were used for these tests. As seen, PSL-particle reentrainment from the polypropylene filter decreases with increasing relative humidity. For supermicrometer particles, the decrease in reentrainment may exceed 2 orders of magnitude for the indicated range of relative humidities, while it is less than one decade for submicrometer particles. We attribute the high decrease in reentrainment to the increase in liquid bridging between the particles and the surfaces they adhere to. Liquid bridging increases the adhesion force between particle and surface (Zimon, 1982). The reentrainment of 1 μm particles is about 0.25% at 22% relative humidity, and decreases to about 0.04% at a relative humiditv of 50%.

CONCLUSIONS

For the tested fibrous filter material, reentrainment of 5 μm and smaller PSL particles occurred only at air velocities that are at least 1.5 decades higher than the 6.6 cm/s fileration velocity that is typical for breathing through a half-mask respirator under medium work load conditions. For irregularly shaped particles and particle agglomerates, reentainment may occur

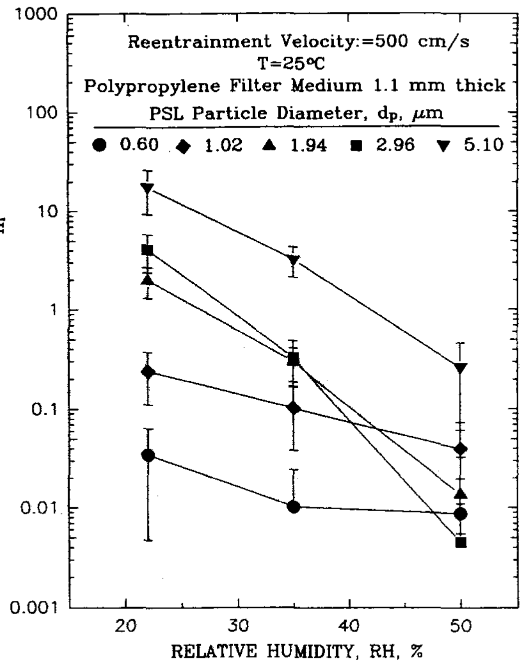

FIGURE 9. PSL particle reentrainment from electrically charged polypropylene filters at different relative humidities. The reentrainment flow direction is opposite to the filter loading direction.

at lower reentrainment velocities. For the test conditions, particle reentrainment increases approximately with the square of particle size and reentrainment velocity, and decreases with increasing relative humidity. The material composition of the particles and filters also affect the degree of reentrainment. While electrostatic charges on the filters significantly increase the collection of submicrometer particles, particle reentrainment is only slightly impeded by the embedded charges.

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