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FILTRATION OF AEROSOLS*

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Abstract—Filters for aerosols and for particles in liquids work by three similar mechanical processes but, in each, the range of particle size over which the mechanism is effective differs from air to liquid; there are also substantial differences in the ways in which electrical forces act. The design of air filters has followed various routes dictated by practical needs. Apart from cleaning air there are other situations in which an understanding of particle deposition is essential, not on filter elements but in machinery, on aircraft, on water droplets in nature and in industrial situations, on plants and vegetation and in the respiratory tract. The basic processes are the same as those operating in filters but fluid mechanical factors are often very different. Particle transport, which is a generalization of filter penetration by aerosols, is of wide significance on a global scale.

INTRODUCTION

In some papers on filtration it is not always clear, at first, whether particles in the gas or liquid phase are to be dealt with. It makes quite a lot of difference, as a comparison of the behaviour of airborne and water-borne particles demonstrates. This is an instructive exercise which is worthwhile, even when the primary interest is in air filters. Let us first consider the three mechanical processes by which particles are deposited in filters, inertia, interception and diffusion. Viscous flow past the filtering elements and relative to the particles will be assumed, since this is usual in efficient filters. As a deposit builds up in a filter the filtration tends to be taken over by the bed of deposit instead of the elements of the filter, especially in filters for liquids; clean filters will be discussed to begin with.

INERTIAL DEPOSITION

The relaxation time of a particle of mass m, radius a and density ρ, moving relative to a surrounding fluid of viscosity η, is

$$\tau = \frac{m}{6\pi a\eta} = \frac{4a^2\rho}{18\eta}. \qquad (1)$$

A particle comes to rest in a time of this order after removal of the force that was maintaining relative motion. The relaxation time of a particle is 55 times greater in air than in water, this being the ratio of the viscosity of water to that of air. Hence particles carried through a filter in water depart much less from the streamlines of flow than they would if carried by air at the same face velocity, V. Inertial impaction on the elements of a filter depends on the Stokes number of the system.

$$St = \frac{\frac{1}{2}mV^2}{6\pi a\eta V\frac{D}{2}} = \frac{\tau V}{D} = d_s/D, \qquad (2)$$

where D is the size of the filter element, for example a paper fibre or a sand grain, and d_s is the stop-distance of the particle. Impaction is only important in filters when

$$St > 0.5. \qquad (3)$$

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For example, if $St = 0.5$, $V = 10$ cm/sec and $D = 3 \times 10^{-4}$ cm, then equation (2) gives $\tau = 1.5 \times 10^{-5}$ sec. On substitution of this value in equation (1) the radii of the particles come out to be $a = 2.2 \times 10^{-4}$ and 16×10^{-4} cm in air and water, respectively. Only for larger particles than these is inertial impaction a significant mechanism causing particles to make contact with the elements of a filter.

Calculation of the efficiency of a fibrous filter is carried out by determining, theoretically, the efficiency with which a single fibre filters particles by the different mechanisms, including allowance for the effect of neighbouring fibres on the flow field past the single fibre. There is a standard method of calculating the efficiency of the whole filter from the single fibre efficiency (Davies, 1973).

Theoretical calculations of the single fibre collision efficiency, E_{RI}, have been made on the basis of massive point particles which touch the fibre when the trajectories of their centres pass within one particle radius of the surface of the fibre, this being a combination of interception efficiency, E_{R}, and inertial efficiency, E_{I}. The motion of the centre point of the particle along its trajectory is calculated by employing the particle radius, to obtain the drag, combined with the field velocity resolutes at points where the centre of the particle is located. Hydrodynamic repulsion as the particle approaches the surface of the filter element is seldom allowed for, supposing that the particles have sufficient inertia to make contact. The particle thus hovers between being a massive point and geometrical sphere according to the exigencies of the calculation. Another factor which is neglected is the dragged mass of fluid which adds to the particle mass during acceleration; this is not appreciable in viscous flow.

INTERCEPTION

Particles of small mass are assumed to move along streamlines and to touch the filter element when the streamline approaches within one particle radius. This is purely geometrical and is calculated from the stream function, if it is known. Owing to hydrodynamic repulsion an inertialess, large particle could not touch a filter element, were it not for the Van der Waals force of attraction; at the long range which would be relevant, this attraction would be less effective in water than in air. Single fibre interception collision efficiency, E_{R}, is independent of velocity provided the flow through the filter is viscous. It is then the same for identical water and air filters. In general

$$E_{\mathrm{R}} = f(c, a/R), \tag{4}$$

where c is the volume of the fibres or filtering elements divided by the volume of the filter (1-porosity). If the filter elements are much smaller in radius than the particles, hydrodynamic repulsion is negligible. Taking the filter to consist of cylinders of radius R, transverse to the flow, then the particles travel in straight lines past the cylinder and the interception collision efficiency is very high

$$E_{\mathrm{R}} = \frac{a+R}{R} \simeq \frac{a}{R}, \qquad a \gg R. \tag{5}$$

This is also true at lower values of a/R if the particles are heavy so that they experience little hydrodynamic repulsion.

This behaviour has been applied to sampling aerosols with very fine spiders' threads (0.5 μm diameter) which provides a "captive" aerosol, the individual particles of which can be studied over a period of time (May, 1967; Druett and May, 1968) (Fig. 1).

DIFFUSION

Particles, when small, execute Brownian motion which causes them to diffuse down a concentration gradient. A concentration gradient exists when the particles adhere to the filter elements after collision. The coefficient of diffusion of particles is given by Einstein's relation

$$\nabla = \frac{kTC}{6\pi a\eta}. \tag{6}$$

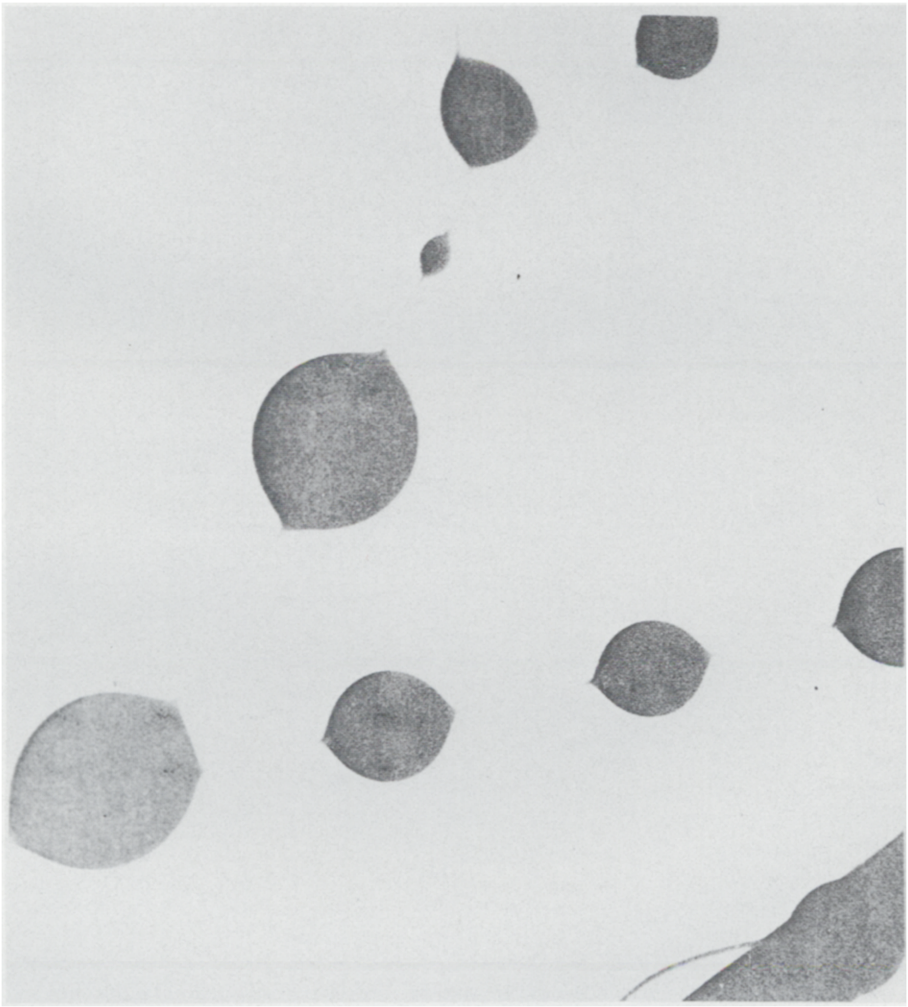

Fig. 1. Captive aerosol. Droplets collected on very fine fibres can be retained as if airborne for studying rate of evaporation, viability of bacteria and fungi and other properties.

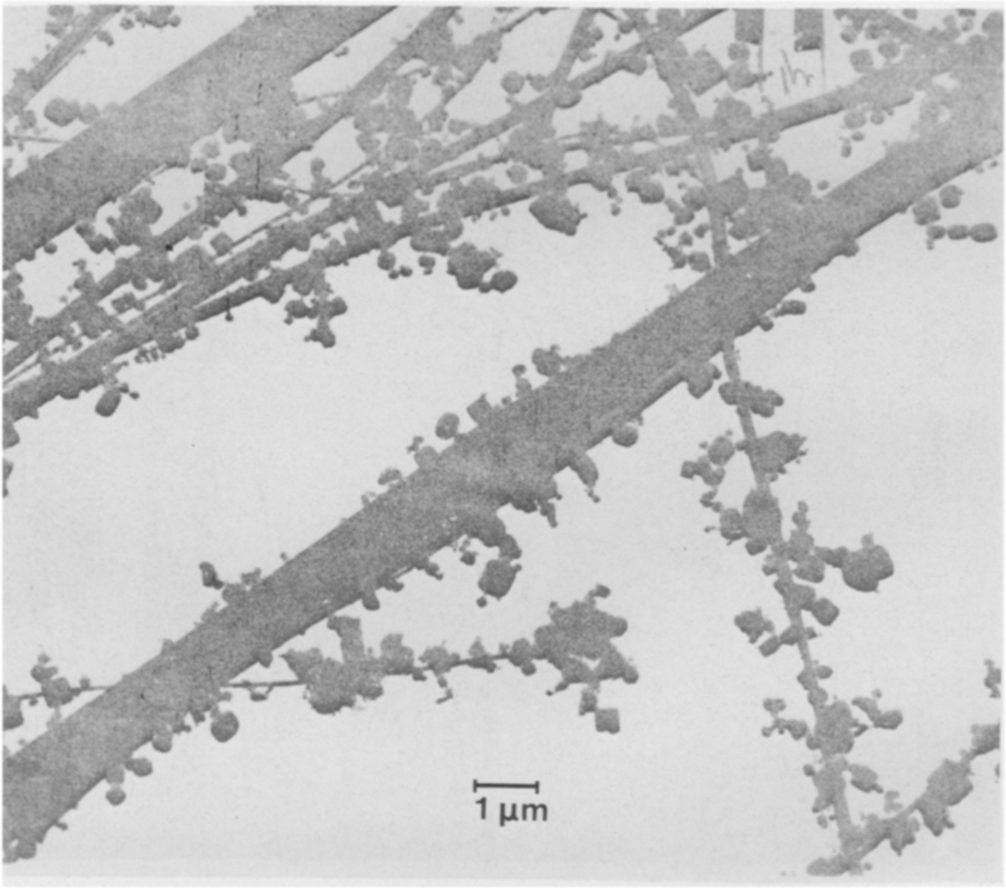

Fig. 4. Particles of sodium chloride in a filter. Note the more efficient deposition on the fine fibres and the beginning of dendrite growth.

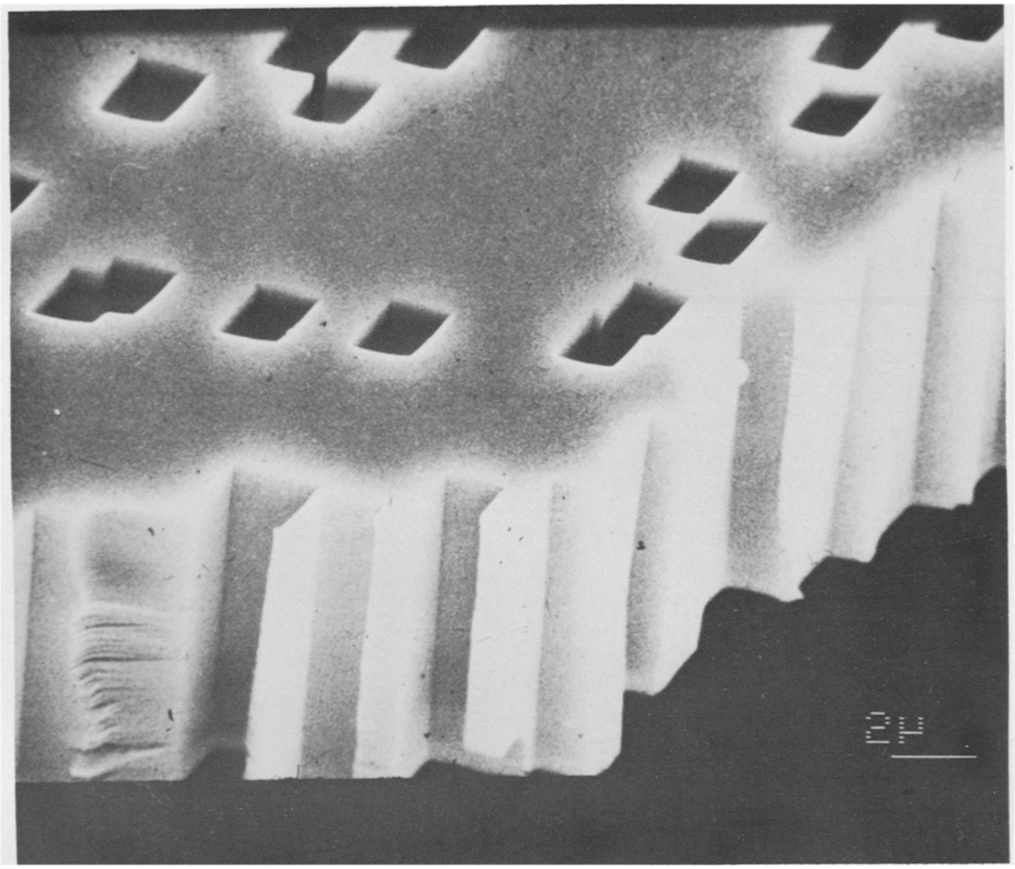

Fig. 5. Mica Nuclepore filter; the pores are drilled by fission fragments and etched to size with hydrofluoric acid (Vater *et al.*, 1980).

C is the Cunningham–Knudsen–Weber–Millikan drag factor which is one for water, since the molecules of a liquid are in contact, but increases as the particle size decreases in gases.

In air, C/a increases rapidly as a decreases so that the diffusion coefficient of particles rises increasingly rapidly with decreasing size; in air filters, therefore, deposition due to diffusion, or Brownian motion, is very effective for small particles. In water the value of ∇ is inversely proportional to the particle radius, since C is always unity and the diffusion coefficient in water becomes relatively smaller and smaller, compared with the value in air, as the particle size decreases. This is shown in Table 1 calculated for 20°C and air at 1 atm. pressure.

In air filters diffusion is an increasingly important deposition mechanism as particle radius decreases below 1 μm. In water it is only just becoming appreciable for particles of 0.01 μm radius.

Table 1

a (cm)	C	∇_{air}	∇_{water}	$\nabla_{\text{air}}/\nabla_{\text{water}}$
10^{-4}	1.08	1.25×10^{-7}	2.15×10^{-9}	58
10^{-5}	1.88	2.2×10^{-6}	2.15×10^{-8}	102
10^{-6}	11.56	1.35×10^{-4}	2.15×10^{-7}	625

Since deposition by impaction and interception increases with increasing particle size, while deposition by diffusion increases as particle size becomes smaller, it follows that there is a size range for minimal deposition in all mechanical filters. This was appreciated by Freundlich (1922) and explained by Kauffman (1936) (Fig. 2).

RETENTION OF PARTICLES ON THE FILTER ELEMENTS

Whether a particle adheres to a filter element after colliding with it, or becomes detached, depends partly on the fluid mechanical drag on the particle and partly on the force of adhesion. The fluid mechanical drag in water is at least 55 times that in air.

The basic force of adhesion is the London–Van der Waals force, due to interaction between transient electrical dipoles in the particle and the filter element. This force has two components which in the idealized case of a sphere on a plane are (Israelachvili, 1974)

$$F_{\mathrm{N}}\,(\text{normal}) = \frac{1.35 \times 10^{-12} R}{6H^2} \quad [\text{dynes}],$$

$$F_{\mathrm{R}}\,(\text{retarded}) = \frac{2\pi}{3}\,\frac{0.97 \times 10^{-19} R}{H^3} \quad [\text{dynes}], \tag{7}$$

where H is the separation at the "point of contact" and R is the radius of the sphere which has to be interpreted, not as the radius of the particle but that of the very much smaller excrescences on the particle which constitute one or more "points of contact". The normal force alone is effective over separations, H, up to 12 nm, while beyond 50 nm the retarded force operates hence, as far as adhesion of particles on fibres in filters is concerned, it is probably the normal force which matters; for a radius $R = 10^{-4}$ cm its magnitude is about 10^{-2} dynes for a separation $H = 4 \times 10^{-8}$ cm (4 Å) decreasing as $1/H^2$. With such a close contact it is improbable that the Van der Waals attraction would differ much for filters of air or water.

In an air filter with a face velocity of 10 cm/sec the drag on a stationary particle is 10^{-2} dynes when, as a first approximation, using Stokes' law

$$a = \frac{10^{-2}}{6\pi(0.00018 \times 10)} = 0.28\ \text{cm}.$$

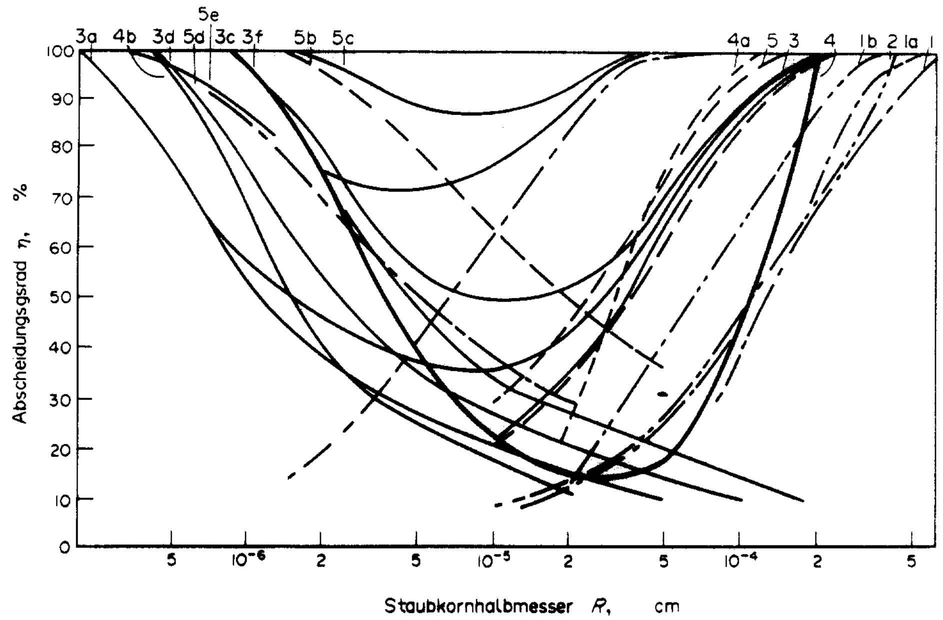

Fig. 2. Kaufmann's (1936) plots of filtration efficiency against particle radius showing minima at 0.05–0.3 μm radius, depending on the type of filter.

Actually for a particle of this size the drag would be greater than the Stokes' law value, but if this is corrected by means of the Reynolds number/drag coefficient relation, $a = 0.14$ cm is obtained as the radius of a particle below which the Van der Waals force would suffice to hold it against a 10 cm/sec air velocity with a contact region of radius $R = 10^{-4}$ cm. This is so large a particle that it is evident that in high quality air filters with a low face velocity all particles which touch the filter elements would be retained by the Van der Waals force. The analogous limit for a water filter is 2.5×10^{-3} cm. At higher velocities particles may bounce on first contact and either pass right through the filter or be retained after several bounces, since the velocity of the particle may be decreased (Davies, 1974).

If the particles, or the surface on which they deposit deform, the area of contact will be increased, improving the force of adhesion. Surface tension or electrostatic attraction may supplement the Van der Waals force.

ELECTROSTATIC EFFECTS IN FILTERS

The concentration of ion pairs in air is normally of the order of $1000/\text{cm}^3$. In water it is at least 10^{13}. This means that per molecule there are at least 10^7 more ions in water than in air. The dielectric constant of water is 80 times that of air. These two factors explain the formation of electrical double layers on particles and on filter elements in aqueous solutions which stabilize the particles against the aggregation with one another and with the filter elements, due to electrostatic repulsion. For effective filtration the double layers need to be disrupted. This is the lyophobic colloid situation where flocculation can be induced by reducing the thickness of the double layer by adding polyvalent ions following the Schulze–Hardy rule and the Hofmeister series (Verwey and Overbeck, 1948). This gives the Van der Waals force the chance of bringing the particles into contact. In fact, there is an intermediate situation in which the retarded force may assist in balancing the electrostatic repulsion when the particles are not quite in contact, as in dilatancy, which may be important in aqueous filtration.

Aerosol particles have no electrical double layer since sufficient ions are lacking and, in the absence of a high dielectric constant, the electrostatic attraction between opposite charges is too strong for the thermal motion of the ions to prevent them making contact. Electrical filters work by Coulomb attraction.

One hundred years ago Oliver Lodge showed that dust could be precipitated from air electrostatically. The first electrical air filters were made just over 50 years ago by Hansen, in Denmark, using what would be a very poor filter pad of coarse fibres, but which were dusted with powdered resin particles, each carrying an effectively permanent negative electric charge. These filters are excellent and have low air resistance; they have been widely used in personal respirators and other situations.

The particles of colophony resin are about 1 μm in size and have quite exceptional resistivity ($\sim 10^{21}$ ohm cm) which explains both the long life of the filters and their failure if discharged in some way. The electric fields issuing from the resin particles and terminating on the relatively conducting wool fibres are strong enough at a distance of about 3 μm from the fibre surface to induce charges on aerosol particles which convey them to the wool or resin surfaces. The wool alone has a filtering efficiency of only about 50 % whereas that of the resin wool filter is 99.99 % (Walton, 1942; Feltham, 1976, 1979; Gillespie, 1955). The distance between wool fibres averages at about 50 μm. The prospect of traversing the entire interfibre distance, instead of only 3 μm of it, with an adequate electrical field, coupled with difficulties in the supply of colophony resin encouraged a search for synthetic materials and theoretical studies of electrical filtration.

A number of tests on polymers indicated that polystyrene had the highest resistivity and carried considerable charges of both signs on its surface (Van Orman and Endres, 1952); tests with filters made of polymer-coated glass fibres and polymer fibres gave encouraging results. Charging the aerosol particles up to ±300 electrons by passing them through a corona discharge considerably improved filtration efficiency (Lundgren and Whitby, 1965). It has been found possible to manufacture electret fibres by exposing sheets of polypropylene to a corona discharge which injected charges into the body of the plastic; the sheets carried positive charges on one side and negative on the other. The sheets were then cut into fibres of rectangular section which were, in effect, linear dipoles and made into filters (Van Turnhout *et al.*, 1976).

Filters have also been constructed of frames carrying double windings of fine wires (0.01 cm diameter) well insulated from one another and charged to 600 V. With such fine wires the field between them is inhomogeneous and moves charged and uncharged particles equally. As the charged particles build up on the wires the field strength between them falls; before this goes too far the field is reversed which produces a field stronger than before since the charges on the deposited particles aid it. The next layer of particles to be deposited has opposite polarity to the preceding layer so the deposit is tightly bound. Further reversals of the field are made as required. This is claimed to be the most efficient type of electric filter; it has low resistance and is specially treated to make it impervious to moisture (Walkenhorst, 1969) (Fig. 3).

Theoretical work on electrical filtration has included calculations of the deposition of particles, charged and uncharged (Natanson, 1957), flowing past a fibre in a uniform electric field (Zebel, 1965, 1969). The fibre becomes polarized, according to its dielectric constant, which leads to efficient deposition as was verified experimentally using very tenuous perlon stocking material (Zebel, 1964). Some of this theory is applicable to magnetic filtration which has industrial applications. A recent theoretical study of filters made of electret, or line dipole fibres, leads to expressions for the trajectories of both charged and uncharged particles and for single fibre filtration efficiencies from which it is possible to derive the efficiency of an entire filter by established methods (Brown, 1981). Hitherto this has been applied to filters in which the fibres are mostly transverse to the airflow, with due allowance for screening, this best being done by the "Fan" model (Davies, 1973; Kirsch and Stechkina, 1978). A study is now available for electrostatic filters with the fibres parallel to the airflows which offers some advantage over the usual arrangement if the practical difficulties of manufacture can be overcome (Brown, 1982).

The effect of adjacent fibres on the flow pattern past a transverse single fibre has been of basic importance to the development of theories of mechanical deposition of particles in

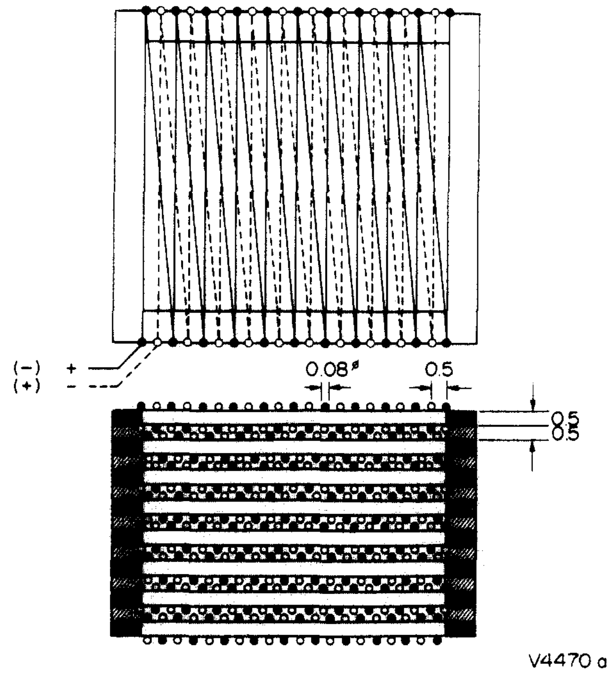

Fig. 3. Filter frame, due to Walkenhorst (1969) with a double winding of oppositely charged fine wires at 600 V.

fibrous filters. Henry and Ariman (1981) have worked out a theory for the effect of neighbouring fibres on the electrical field in a fibrous filter in which the images of six cylinders surrounding a single cylinder of the same radius are shown to decrease the single fibre efficiency of electrical filtration.

For particles above 0.2 μm radius the enhancement of filtration by an electric field external to the filter is mainly due to polarization of the particles. A method of calculating directly the critical particle trajectories, dividing particles which miss a transverse fibre from those which collide with it, has been described by Banks *et al.* (1983). It depends on the radial velocity component of the particle becoming zero on contact for inertialess particles.

A useful collection of papers on fine particle filtration has been edited by Englund and Beery (1975).

FILTERS FOR VARIOUS USES

Cloths wrapped round the nose and mouth to protect workers from dust were recorded in AD 50. The first respirator with a filter appeared in 1814. Quite complicated filter containers designed by John Tyndall, the first experimenter with aerosols, were used with facepieces by firemen in 1868. Two world wars resulted in great improvements in respirator efficiency; the main aims were low breathing resistance, during active movement, and high filtration efficiency against particles of the most penetrating size, ~ 0.2 μm diameter or less for very good filters (Davies, 1973). Recently, powered respirators have come into use in which a small positive pressure is maintained in the facepiece, thus avoiding leakage round the edges during inspiration (Kugler and Simpson, 1981).

Large filtration plants consist of sets of units incorporating filters which are basically the same as those used in respirators (White and Smith, 1964). These are used to sterilize air for medical and associated purposes, to feed clean rooms and to protect manufacturing processes.

For all requirements needing very high filtration efficiency and large throughput with low resistance the use of fibrous materials and face velocities of the order of less than 10 cm/sec is universal. There is a big market for filters of less rigorous performance in which particles below 1 μm do not cause concern. Cheaper, coarser fibres and high face velocities are the rule; non-fibrous porous materials are also used. Such filters are found in air conditioning and ventilating systems and keep out pollen, fungal spores and much dust, but cigarette smoke passes through; they are also used on the intakes of internal combustion engines. Fibrous filters made of 3 μm diameter fibres of alumina and of zirconia will function at temperatures up to 1400 and 1600°C, respectively (Symes, 1974).

In chemical filtration of liquids the residue is often required and its bulk is much greater than that of the filter so that it ends up as the filtering medium. The deposit is required in air filters which are used for sampling aerosols but from filters for cleaning air it is seldom recovered; the rise in resistance precludes the use of filters which have become substantially clogged with unwanted residue. The lifetime of a filter is important. In an unused air filter the porosity is high and the air spaces are many times larger than the particles it is designed to trap. In use, the deposit builds up on the fibres, often as dendrites or chains of particles which stand out from the surface of the original fibres and very much improve the filtering performance as well as raising the resistance (Fig. 4). There have been theoretical and experimental studies of the growth of dendrites (Payatakes and Tien, 1976; Bhutra and Payatakes, 1979; Kanaoka *et al.*, 1980). Some of the reasons for the formation of chains of particles were discussed by Beischer (1939).

Filters are important tools in the study of aerosols but the measurement and analysis of deposited particles is difficult with fibrous filters. Membrane filters, which had been in use for a long time for filtering water were adopted for aerosol analysis about 25 years ago. Microscopic size analysis of the deposit on these filters is possible so they are useful for sampling aerosols. They are available with graded pore sizes from 0.1 to 5 μm in several membrane materials which are compatible with many chemicals. The pores are interconnected and form an open honeycomb structure.

The pathways through membrane filters are tortuous and not easily dealt with mathematically. However, in 1968, a new type of filter was produced with uniform cylindrical pores perpendicular to the membrane. These Nuclepore filters were made by perforating plastic film about 10 μm thick with collimated beams of fission fragments of energies around 0.8 MeV/a.m.u. and etching the holes to the required size with sodium hydroxide solution. The holes are uniform in size, of nearly circular section and number 10^5–10^7/cm^2. These filters make useful diffusion batteries for very fine aerosols. They can be used up to 70°C.

Quite recently a development of this idea has resulted in the production of mica Nuclepore membrane filters which work satisfactorily up to 500°C. Sheets of mica 40–50 μm thick are perforated with highly collimated heavy ion beams up to 10 MeV/a.m.u. in a heavy ion linear accelerator. They are then etched in 48 % hydrofluoric acid to the desired pore size (Fig. 5). The final holes have a parallelogram cross section and smooth walls; an additional etch with hot caustic soda solution, at 130–150°C for 6 hr, gives the pores a rounded entry (Vater *et al.*, 1980).

Larger filters of sand have been proposed for safeguarding the fast breeder nuclear reactors of the future which employ considerable quantities of sodium as a heat transfer agent from the reactor core to the steam generator. An accident could result in the release of sodium containing aerosol, possibly with radioactive material. Experimental work, in which the fumes from a 1 m^2 sodium fire (0.6 mg/cm^2 sec Na) were passed through 2 m^3 of sand, showed that it was necessary to adjust the packing of the sand bed according to the flow rate in order to achieve low penetration and high loading capacity. The flow through the bed was downwards; the top layer of sand was coarse (~ 3 mm) followed by several layers of finer sand of decreasing porosity, with a thick open layer of coarse sand at the bottom. Finer grades of sand were necessary for low flow rates to maintain performance. The loading capacity was much better than that of glass fibre filters which suffer from chemical attack by sodium oxide. The bed could carry up to 600 g/m^2 maximum with 80 cm WG pressure drop (Böhm and Jordan, 1976).

Theoretical work on these filters has been performed by Lee (1981) and Dietz (1981) has studied electrical action in such filters.

Concern has been expressed that the present generation of pressurized water reactors, containing the equivalent of 10,000 tons of radium cooled by water at 2000 psi and 350°C, might destroy sand-bed filters in the event of an emergency, due to the abundance of steam. A new idea for a large filter is to construct a bed of rock fragments a few centimetres in size; unlike sand this cannot clog in the presence of condensing steam which drains away. Experiments in Sweden on this system have been successful; good efficiency and rapid draining of condensed water were found. With face velocities below 5 cm/sec the penetration was low and was diminished by the presence of the water. The action did not seem to depend on diffusiophoresis but could have been aided by condensation on the particles increasing their size (Ström and Chyssler, 1983).

FILTRATION GENERALIZED

In a sense, any process which removes particles from the fluid-borne state can be described as filtration; sometimes this removal is desirable, at others it is not. The most familiar process is sedimentation under gravity which is not important in filters of high efficiency since, in practice, they are protected by prefilters of relatively low efficiency which remove the coarser particles and prevent them from becoming prematurely clogged. The flow in high efficiency filters is viscous and streamline but in other situations involving the separation of particles the flow may be at higher Reynolds numbers and possibly turbulent.

When aircraft flew at lower altitudes than they now do, icing of the leading edges of the wings due to the impact of supercooled water drops was a danger. Calculations of the trajectories of water droplets as the plane flies through clouds were carried out in 1940 and enabled the minimum size of drop which presented a risk ($\sim 30\,\mu$m diameter) to be determined and the rate of accretion of ice to be estimated from meteorological data (Taylor, 1940; Glauert, 1940). When mustard gas was first dispersed as airborne droplets in the Abyssinian war precisely similar calculations were necessary to evaluate the accuracy of sampling methods which, as a result, were used in field experiments at Porton to comprehend the nature and extent of the threat from such weapons. Most of this work was done for ideal fluid flow and Stokes' law drag of the droplets, repeating the assumptions which had been made ten years earlier by Albrecht (1931) in the first analysis of the mechanism of fibrous filtration in which ideal flow round a 20 μm fibre is not so good an assumption as it is for the wing of an aeroplane.

Later, the advent of gas turbines raised problems because they are filters of atmospheric particles and of self-produced particles which impinge on and erode the blades. Stokes' law is inadequate in this situation but ideal fluid flow gets by. An enormous bulk of trajectory calculation, aided by the computers which were not available for the icing and sampling problems, has been carried out in this field (Institution of Mechanical Engineers, 1981), Fig. 6.

Water droplets, sprayed and falling under gravity, are extensively employed for removing dust both in gas scrubbers and in mining operations. Scrubbers have been incorporated in centrifugal dust separators, cyclones and venturi systems in a wide variety of designs aimed at bringing the dust particles into contact with the water drops at the highest possible Stokes numbers (Calvert *et al.*, 1972). Removal of coarse dust by such methods is effective but particles below 1 μm tend to escape collection and some dusts of this size range are dangerous to inhale. Work on dust suppression in coal mines has shown that sprays of water drops from 0.5 to 2 mm diameter, falling under gravity are effective in removing particles of airborne coal dust which are greater than 10 μm in diameter. High pressure sprays projecting water drops at high velocities (0.1 mm water drops at 3000 cm/sec) collect dust down to 1 μm, but not very well (Walton and Woolcock, 1960). Hence these systems of dust suppression improve visibility in mines and decrease the risk of dust explosion, but give inadequate protection against dust inhalation which causes pneumoconiosis, the dangerous particles being below 5 μm diameter. Excess of water in deep, hot mines is undesirable since high humidity diminishes evaporative cooling of the miners.

Situations in which warm, moist air encounters cold droplets result in the droplets growing by condensation; aerosol particles, if present, are drawn towards the droplets by dif-

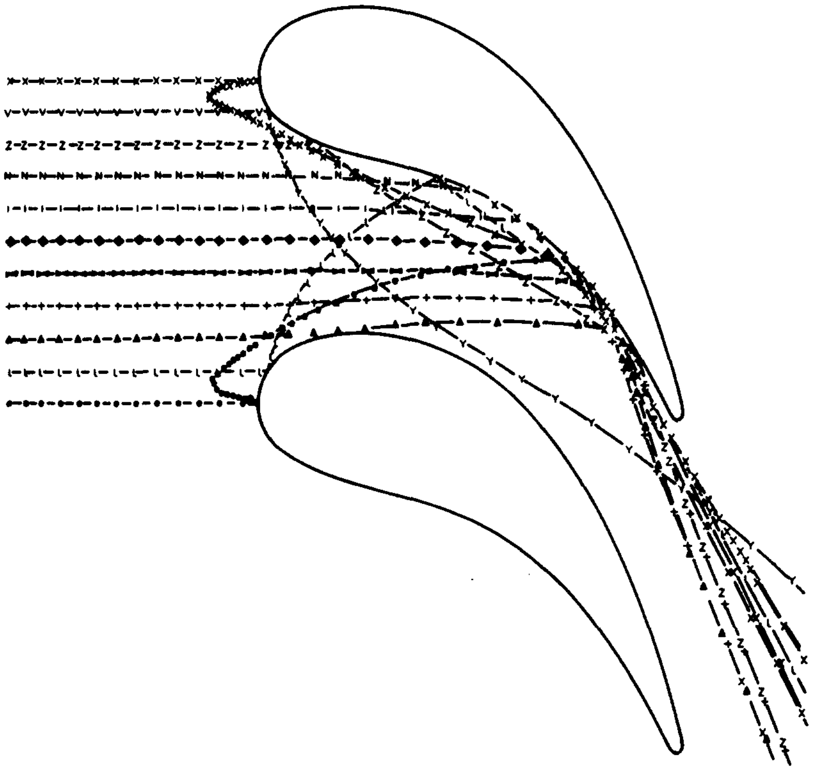

Fig. 6. Calculated trajectories of particles 200 μm in diameter through gas turbine blades showing rebound and focusing on regions of high rate of erosion (Tabakoff and Hamed, cited in Institution of Mechanical Engineers, 1981).

fusiophoresis and Stefan flow so there is an enhancement of scrubbing efficiency. The significance of this in meteorology is uncertain, as is the washout of atmospheric pollution and atmospheric nuclei by rain, the apparent degree of such cleansing of the atmosphere being larger than might be expected from the coal dust results. Possibly the electric charges on rain drops are significant.

The administration of herbicides, pesticides and weed killers in war and peace involves filtration by vegetation. There is an interesting contrast between the behaviour of trees in rain and in mist. Raindrops fall quickly and are collected by the leaves and shed outwards, the accumulated water dripping to the ground round the periphery of the canopy. Mist droplets, which are much smaller, hardly move under gravity at all; they are wafted by the wind through the tree branches and leaves, depositing according to Stokes number and, as water accumulates in the "filter", dripping inside the canopy. Hence, as can be seen in London streets, it is dry under trees during rain in summer while the road is wet but on misty occasions (not fine haze which makes the sun look red, but "wet" mist with droplets exceeding 30 μm diameter) the road is dry and it is wet under the trees.

Agricultural sprays have a peculiar history since far more attention has been given to the invention of chemical substances than to their dispersion in ways which enable the plants to act as efficient filters. As a result large quantities of droplets have failed to encounter the desired foliage and there have been numerous accidents and deaths.

Until quite recently high volume sprays were used which were wasteful and were inefficiently deposited, but had the advantage that the deposition, such as it was, was not too much affected by wind. The low volume spray represents the attempt to improve deposition efficiency and dates from 1947 when a spinning disc spray was used to spread DDT on waterways to combat mosquitos (Johnson and Walton, 1947). The high volume sprays gave a wide range of droplet size up to 1 mm diameter; low volume, spinning disc and cup types give nearly uniform droplets of any size from about 30 μm diameter upwards, according to the speed of rotation. Droplets below about 100 μm diameter are not appreciably projected by the spray. Those 100 μm diameter drops of fall under gravity at 25 cm/sec: at 30 μm the rate of fall is only 2.7 cm/sec. The small droplets are suitable against flying insects since they remain airborne for some time and impact on them.

Filtration by plants is largely dependent on wind transport but fall helps a lot for the larger drops if they get among the leaves of the plant with some shelter from the wind (Johnstone *et al.*, 1977). This dependence on the wind, together with sprays delivering too fine droplets, retarded the acceptance of low-volume sprays. Now, calculations known as controlled droplet application, and recommended droplet sizes between 100 and 200 μm diameter make successful spraying more probable. Even so, after 35 years, a recent issue of the *British Farmer* (1982) emphasizes the need for extensive field experiments, and also refers to another idea, reinvented by ICI and due on the market in three years time, which is to charge the droplets or particles electrically which helps to avoid wasteful dispersion. This was tried by Pauthenier *et al.* (1944) using a Felici electrostatic generator to charge a fine wire to a high voltage as a source of ions in the vicinity of a horse drawn powder disperser; it had the advantage of drawing the cloud of particles downwards to the crop and depositing powder on both sides of the leaves.

Another very important filter in which minimal deposition is often best, is the respiratory system (Davies, 1981). From most filters it differs considerably because the airflow reciprocates through a system of conducting airways which constitute a dead space of about 200 cm^3 volume. There are some 25 orders of branching starting from the nose or mouth, through the single trachea to some 12,000 terminal bronchioles. The conducting airways are followed by the respiratory air spaces which have a volume of about 3000 cm^3 and terminate in 5×10^8 alveoli about 150 μm in size over the surface of which gas exchange proceeds.

The filtration performance depends very much on the breathing pattern and on particle size. Particles which deposit least during normal breathing are about 0.5 μm (unit density) in diameter, the deposition being about 10%, all in the respiratory air spaces and none in the dead space. Unlike efficient fibrous filters the sedimentation of particles is important in the lungs, because the size of the alveoli is many times greater than the size of the filter fibres. Above 0.5 μm, particles deposit increasingly in the dead space airways by sedimentation and impaction. Below 0.5 μm diffusion takes over. Interception is not important for particles of compact shape, since the airways are too large, but it is an important mechanism for fibrous particles.

A considerable amount of experimental work and theory, dating from Findeisen (1935), has been devoted to lung deposition but there are still some uncertainties. This knowledge is very important in problems of occupational health in dusty occupations, in the transfer of airborne infection and in aerosol therapy for certain lung diseases.

Finally, we have the surface of the earth as a filter with loss by sedimentation, washout, impaction on plants, forests, buildings, mountains, thermal deposition on ice and snow and distribution of the remaining airborne particles by complicated wind systems. Observations of global aerosol movements and their relation to local and continental weather are now beginning to multiply (Murgatroyd, 1969); they call for measurements of concentrations and chemical identification down to ng/m^3 levels. From them the origins, local, marine and anthropogenic, can be sorted out. It is evident that surprisingly long-distance transport is common, even for quite large particles from the Sahara (Junge and Jaenicke, 1971). Arctic haze contains quite a lot of sulphate. Northern hemisphere industrial activity is doubling every 15–20 years which indicates a density of haze in 50 years from now which could cause significant heating of the polar atmosphere (Rahn, 1981). Balances of production, deposition, transport and local concentrations are difficult to calculate, but this is evidently a top priority (Jaenicke, 1980).

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