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Particle Chain Formation in Aerosol Filtration With Electrical Forces

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It is an experimental observation that aerosol particles captured by fibers in filters tend to form branched particle chains, called dendrites, rather than to distribute themselves evenly along the surface of the fibers (Watson, 1946; Leers, 1957; Billings, 1966; Yoshioka et al., 1969; Barot 1977). These dendrites are apparently better aerodynamic targets than the bare fibers. Models have been proposed to account for the formation of these deposits (Radushkevich, 1964; Yoshioka et al., 1969; Payatakes and Tien, 1976; Payatakes, 1976*a*, *b*, 1977), and some numerical simulations involving particle trajectories have been made to study the mechanisms by which the dendrites may be formed (Tien et al., 1977; Wang et al., 1977; Kanaoka et al., 1978). These simulations, made in a two-dimensional plane, incorporate the ideas that previously collected particles block out or shield portions of the collector from further use, and that particle interception is crucial for formation of the dendrites.

These numerical simulations that show dendrite growth in two dimensions do not consider electrical forces. It has been argued, however, that electrical forces are involved in the formation of chainlike aggregates on fibers (Billings, 1966) and on filter cloth (Frederick, 1974; Penney, 1977), although Payatakes (1976*a*) cites laboratory evidence for dendritic growth in liquid systems in the absence of long range electrostatic forces.

The simple numerical simulations described in the present note, carried out during some earlier studies of particle capture on fibers and droplets using electrical forces (Nielsen and Hill, 1976*a*, *b*; Nielsen, 1978*a*, *b*) and independent of those by Tien et al. (1977), were made to examine the formation of particle chains when electrical forces are intentionally invoked to improve particle collection efficiency. The results illustrate that a central electrical force increases the number of dendrites and the area they cover, but that short range forces between approaching particles and dendrites do not affect dendrite growth very much.

The simplest system to examine involves an attractive coulombic force between a charged circular fiber and oppositely charged spherical particle moving in a potential flow with negligible inertia according to the equation of motion (Nielsen, 1978*a*):

$$X_o = R \sin \theta (1 - R^{-2}) + K_c(\theta - \pi). \qquad (1)$$

The second term in Equation (1) is the stream function for potential flow around a cylinder, X_o is the initial particle position, and K_c is the electrical force parameter or dimensionless mobility for the coulombic force, which falls off as R^{-1}. Equal sized particles ($\mathcal{R}=0.04$) were located randomly and with uniform probability along the line X_o and, following Equation (1), were subject to capture one at a time, either by the cylindrical collector or by particles previously collected, or else swept downstream. Particles are captured only in a single plane, strong particle adhesion is assumed and the primary coulombic force and local flow field are assumed to be unaffected by the dendrites.

With no electrical forces present ($K_c=0$), particles follow the flow streamlines and are captured only by interception. Since the trajectories tend to parallel the fiber surface, shadows cast by the first-captured particles prevent the fiber surface from capturing particles farther downstream. But once initiated, the dendrites, and hence collection rate, grow as a chain reaction. In the experiment for this case, only two dendrites were formed (Figure 1), each growing from one of two particles captured by the fiber. This growth mechanism is identical to that described by Tien et al. (1977).

With the coulombic force [Equation (1), $K_c \neq 0$], chain initiation can occur anywhere on the fiber surface with equal likelihood, and initially many short chains are formed (Figure 2). However, blocking or shadowing of some chains by others causes some chains to terminate and others to dominate the collection. Although net particle collection occurs at a constant rate and not as a chain reaction, individual dendrites grow at a rate proportional to the amount of particle flow not lying within particle shadows that a dendrite sweeps. As a result, deposition on the downstream half of the fiber becomes increasingly blocked as upstream dendrites grow. Under the same conditions, point particles would be deposited uniformly over the entire fiber.

In Figure 2, the effect of the dendrites on the local electrostatic force field is neglected, although in fact short range electrical forces arise between the fiber and the approaching particle. For instance, a charged particle approaching a neutral fiber polarizes the fiber and is attracted to it. This force becomes significant when the particle is on the order of one fiber radius away from the surface of the fiber. When the particle passes near a dendrite, the dendrite is similarly polarized, but with this local force extending only on the order of one particle radius away from the dendrite. Similarly, with a charged fiber some of the charge resides on the dendrites, and the otherwise radial electric field lines are distorted near them, curving in obliquely to the dendrite surface. The coulombic attraction for oppositely charged particles extends along these field lines, and the particles are locally attracted to the dendrites.

This localized force was crudely accounted for by simply expanding the effective capture radius of particles in a dendrite from 1 to 1.5 particle radii. Upon interception of the increased capture radius, approaching particles were pulled into actual contact with the capturing particle along their line of centers. The result of using this simulation of short range forces is shown

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in Figure 3 for the same distribution of approaching particles and conditions as in Figure 2. The overall pattern of collection is basically the same, but it has changed subtly: dendrites lean farther forward into the flow and are somewhat longer and straighter for the same number of particles, and contact between neighboring chains is reduced or eliminated. In this experiment, particles are captured only by the localized forces (capture by a dendrite would occur even in the absence of interception), but a dendrite's shadow, caused by the finite size of the particles, still has a much longer range effect and hence appears to remain the primary influence on dendrite growth.

The numerical experiments described here are not of any quantitative use, since only one set of initial conditions is shown, since the velocity field is approximated as potential flow, and since all of the captured particles lie in a single plane. In three dimensions the particle chains would be branched laterally as well, of course, and the slight straightening of chains that occurs in Figure 3 with localized forces should also occur in three dimensions. Growth rates of individual chains depend on the initial conditions and will be different in two and three dimensions. The overall collection rate, however, will be the same in both cases and will also be independent of the flow field as long as the dendrites lie within the envelope of limiting trajectories.

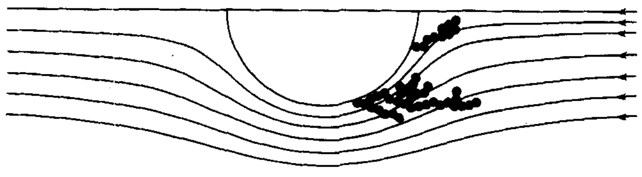

Figure 1. Dendrite formation in collection by particle interception alone with $\mathscr{R}$=0.04. Solid lines are streamlines for potential flow originating from the left.

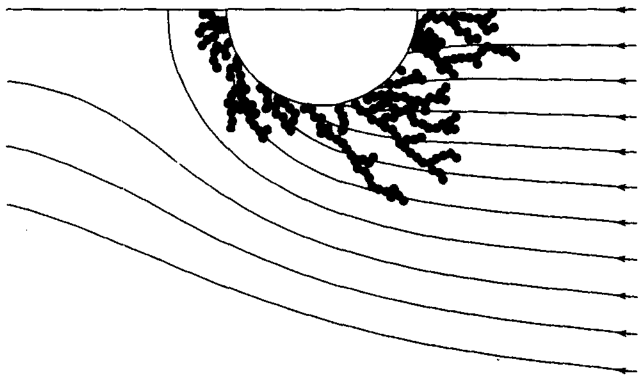

Figure 2. Dendrite formation with a coulombic force for particles in a potential flow field, K_c = −1, $\mathscr{R}$=0.04. Solid lines are particle trajectories, Equation (1).

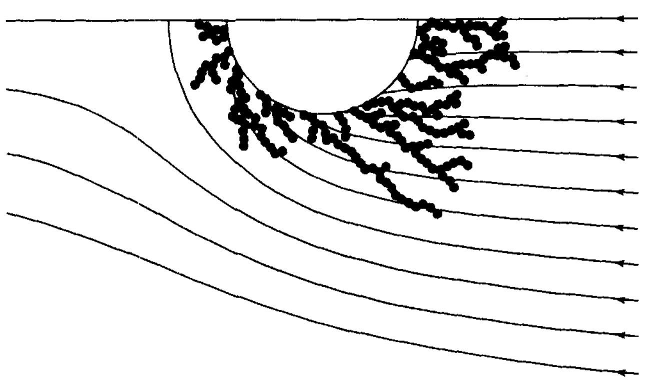

Figure 3. Dendrite formation for the same conditions and initial particle distribution as in Figure 2 but with the addition of simulated short range attractive forces between approaching particles and dendrites.

This study does not resolve the problem of how dendrites in fibrous filters form, but it does indicate that if strong electrostatic forces are involved, for example, from permanent charges on the fibers and particles, dendrites will form over a large area as in Figure 2. Furthermore, such dendrites are not necessarily advantageous to particle collection; in the case of no electrical forces (Figure 1), the fiber efficiency is initially only about $2\mathscr{R}$ and increases greatly as particles are captured. In the case of coulombic force attraction, however, the collection efficiency can be orders of magnitude larger, $-\pi K_c$, and remains at that value until dendrites cross the limiting trajectory. During this period, aerodynamic drag or pressure drop would increase without an increase in collection efficiency.

NOTATION

C = Cunningham-Millikan slip correction factor, dimensionless

K_c = $\rho_c Q_p C/12\pi^2 \epsilon_f R_c R_p \mu U_o$ = coulombic force parameter for cylindrical collector, dimensionless

Q_p = particle charge, coul

R = radial coordinate relative to R_c, dimensionless

R_c = radius of circular fiber, m

R_p = radius of spherical particle, m

$\mathscr{R}$ = R_p/R_c = interception parameter, dimensionless

U_o = free-stream fluid velocity, $m \cdot s^{-1}$

X_o = initial particle displacement from center line relative to R_c, dimensionless

ϵ_f = electrical permittivity of the fluid, 8.854×10^{-12} $F \cdot m^{-1}$ for air

θ = angular coordinate measured from downstream center line, rad

μ = viscosity of the fluid, Pa·s

ρ_c = fiber charge per unit length, $coul \cdot m^{-1}$

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Effect of Electrostatic Fields on Accumulation of Solid Particles on Single Cylinders

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When a particle laden gas flows past a transverse fiber, such as in a fibrous filter, particles are captured first on the surface of the fiber and later on the deposited particles as well. Watson (1946) observed that solid particles tend to build up on the surface of a collector in dendritic form. The rates at which solid spheres accumulate on single fibers and the morphology of particle deposits, in the absence of electrostatic fields, were studied by Billings (1966) and Barot et al. (1980).

The tendency for deposits to grow in dendritic form is a consequence of two intrinsic properties of aerosols: the particles have finite sizes and the particles are randomly distributed in the aerosol stream. When the trajectory of a particle approaching a transverse fiber is intercepted by a particle already deposited on the fiber, the oncoming particle is captured by the deposited particle, and a two-particle chain is formed. Based on these concepts, Tien et al. (1977) developed a general theory for the accumulation of solid particles on an obstacle in a stream of fluid-solid suspension.

In the presence of electrostatic forces, the rate at which particles accumulate on a fiber is markedly increased, but the tendency for deposits to grow in dendritic form remains unchanged. This note presents the results of an experimental study of the accumulation of particles on single fibers and the morphology of particle deposits, in the presence of electrostatic fields.

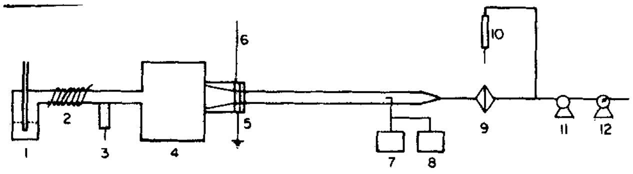

Figure 1. Experimental apparatus.

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EQUIPMENT AND METHODS

Figure 1 shows the general arrangement of the experimental setup used in this study. Monodisperse aerosols of polyvinyl

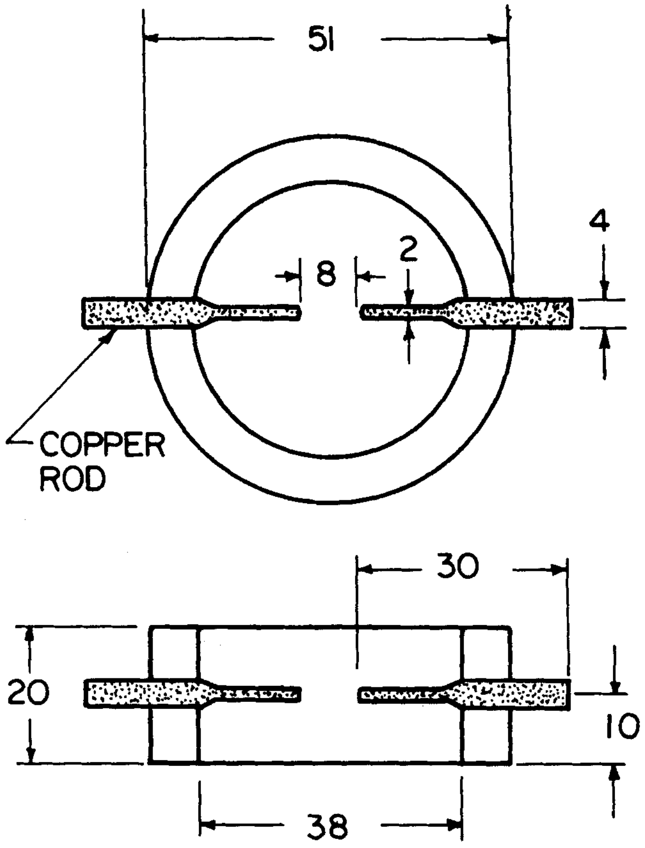

Figure 2. Fiber holder. Dimension in mm.