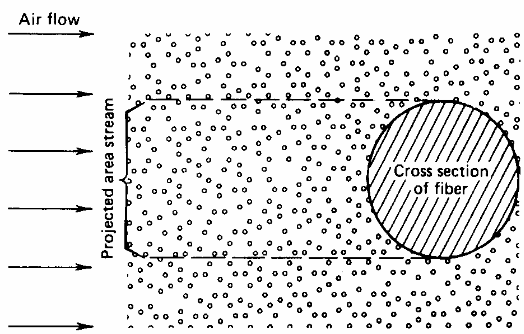
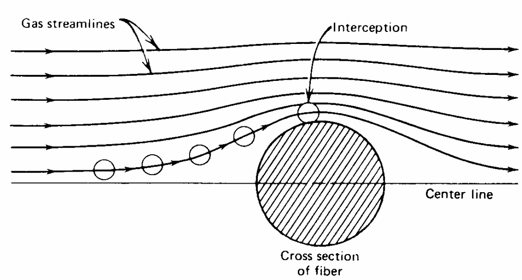
CHARACTERISTICS OF MEDIA FILTERS

Background



Single fiber efficiency, η_T, is the fraction of upstream particles that collects on a fiber. This process is shown in the figure on the left. All particles in the region bounded by the upper and lower lines that extend to the left of the fiber cross section are eligible for collection because they are upstream of the fiber. The fraction of these particles that collects on the fiber as gas passes the fiber is η_T. Particles can collect on a fiber by several mechanisms. Several of these are discussed below.

Particles collect by **interception** if they collect on the fiber without deviating from the gas streamlines. See the figure at the right. Interception is characterized by an interception parameter, R,



$$R = d/d_f \tag{1}$$

where d is particle diameter and d_f is the diameter of the fiber. In addition, the Kuwabara number is important, where

$$\mathrm{Ku} = -\frac{\ln \alpha}{2} - \frac{3}{4} + \alpha - \frac{\alpha^2}{4} \tag{2}$$

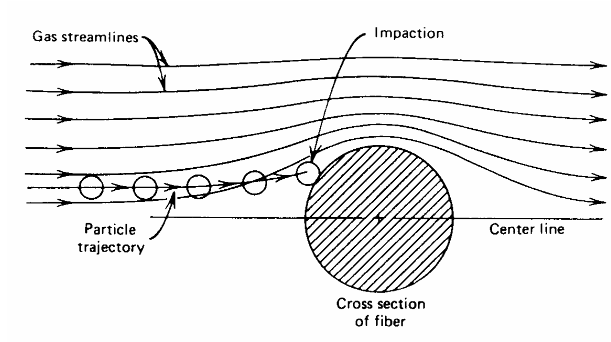
The Kuwabara number is related to flow around the fiber, and depends only on filter solidity, α, where α is the fraction of filter volume that is made up of fibers. In a filter, α might have a value of 0.001 to 0.2, with a typical value of 0.01.

The single fiber efficiency due to interception, η_R, has been represented as

$$\eta_R = \frac{1+R}{2\ \mathrm{Ku}}\left[2\ln(1+R) - 1 + \alpha + \left(\frac{1}{1+R}\right)^2\left(1-\frac{\alpha}{2}\right) - \frac{\alpha}{2}(1+R)^2\right] \tag{3}$$

Note: Drawings that show particle collection mechanisms taken from Hinds, William C., *Aerosol Technology*, 2nd ed., John Wiley & Sons, New York, 1999.

If a particle crosses gas streamlines due to its inertia and collects on a fiber as shown in the diagram to the left, then it is said to collect by **impaction**. Much research has been done to characterize the single fiber efficiency due to impaction in a filter, η_I. One such equation is



$$\eta_I = \frac{J\ \ Stk}{(2\,Ku)^2} \tag{4}$$

where J is given by

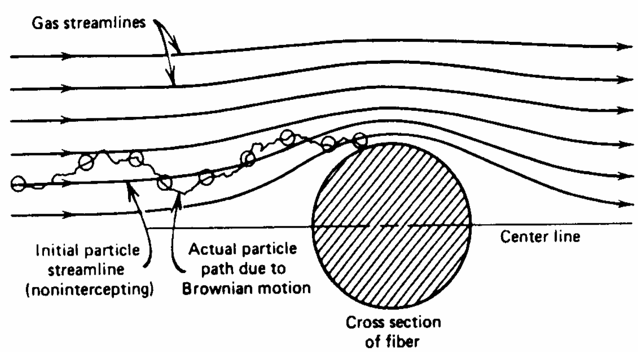
$$J = (29.6 - 28\,\alpha^{0.62})\,R^2 - 27.5\,R^{2.8}, \text{ for } R < 0.4. \text{ and for } R > 2,\ J \cong 2. \tag{5}$$

In Eq (4), Stk is the Stokes number,

$$Stk = \frac{d^2\,\rho_p\,V\ \ C_C}{18\ \mu\ d_f} \quad . \tag{6}$$

Impaction is an important collection mechanism for large particles and high gas velocities.

Particles can also collect on a single fiber by **diffusion**. Brownian motion causes small particles to dart about very quickly due to particle impact with gas molecules. As a result, the particle may touch the fiber if it happens to move in that direction as the gas streamline on which it is riding passes near the fiber surface. See the drawing to the right. Single fiber efficiency due to diffusion, η_D, can be characterized by the Peclet number, Pe,



$$\eta_D = 2.58\left(\frac{1-\alpha}{Ku}\right)^{1/3}\ Pe^{-2/3} \quad , \tag{7}$$

where

$$Pe = \frac{d_f\ V_g}{D} \quad . \tag{8}$$

Here, D is particle diffusivity.

Hinds says that to estimate single fiber efficiency near the particle size where neither impaction nor diffusion is effective, an interaction term must be included to account for collection due to interception of diffusing particles. This effect is represented by η_{DR}, where

$$\eta_{DR} = \frac{1.24\,R^{2/3}}{(Ku\ Pe)^{1/2}} \tag{9}$$

Other collection mechanisms such as gravity and electrostatic effects are also sometimes considered. However, under conditions when gravity is important, impaction is usually more important with the result that the effect of gravity itself can be ignored.

Electrostatic effects can be very important; some filters collect particles *primarily* due to electrostatic attraction. Unfortunately, we have no effective methods to predict single fiber efficiency by electrostatics despite considerable research into the problem. We do know that collection by electrostatics increases for charged particles and for charged fibers. Some commercial filters made by 3M and others rely on a permanent electrical charge embedded in the fibers to provide high efficiency, at least until the fibers become insulated by a coating of collected particles or until the charge becomes neutralized. Fibers charged this way are called "electrets".

Particles can collect by all of the mechanisms discussed above. The single fiber efficiency due to the total of all effects, η_T, is usually taken as the sum of the single fiber efficiencies due to each important mechanism,

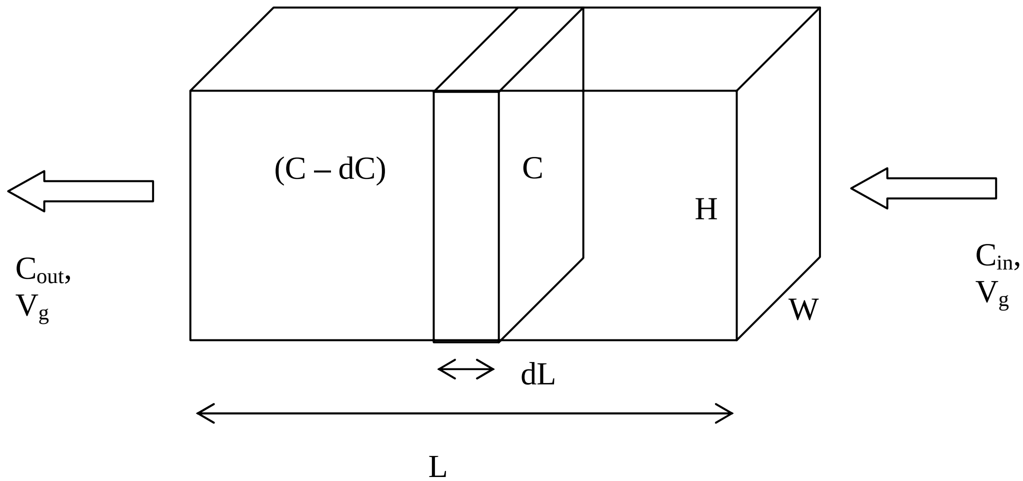
$$\eta_T = \eta_R + \eta_I + \eta_D + \eta_{DR} + \ldots \quad . \tag{10}$$

Eq (10) is correct only if each collection mechanism operates independently, a condition that is best met if all single fiber efficiencies are low. In some cases, several collection mechanisms may be important for the same particle, with the result that the sum of the corresponding single fiber efficiencies is greater than unity. However, any one particle can be caught only once, and if η_T is >1, Eq (10) is incorrect.

A more appropriate way to consider particle collection by more than one mechanism would involve developing a force balance on the particle, where the sum of all forces would correspond to the combined effect of all collection mechanisms. The resultant analysis would be very complex. Often, the simpler approach used in Eq (10) yields satisfactory results, but one must be aware of potential problems if η_T approaches unity.

Overall Efficiency of a Fiber Bed

Here we will develop an equation that will describe particle collection in a media filter. Consider the situation shown in the drawing below, in which dusty gas flows through a bed of fibers that has height H, width W, and thickness L.



Within the filter is a slice with thickness "dL".

First we will make some assumptions about the conditions within the filter:

1. Particle concentration, C, is uniform in any plane perpendicular to the direction of gas flow,

2. Gas velocity, V_g, is uniform throughout,

3. No particle reentrainment or bounce; that is, once a particle comes in contact with a fiber it stays there,

4. All fibers are oriented so that their long axes are perpendicular to the direction of gas flow.

Note that these assumptions are very similar to the ones we made when we considered particle collection in a gravitational settling chamber.

A balance for the rate at which particles pass through the differential slice yields the equation given on the next page. The term on the left side of the equation represents the rate that particles enter the slice from the air. The first term on the right side of the equation is for particles that leave in the air that flows from the back side of the slice. The second term on the right side is for particle accumulation within the slice, where accumulation is caused by particle collection on fibers within the slice. The sign on the accumulation term is negative because particles are *removed* from the air in the slice; that is, they do not *accumulate* there.

$$\overbrace{V_g\, H\, W\, C}^{\text{Rate dust flows into the slice}} = \overbrace{V_g\, H\, W\,(C - dC)}^{\text{Rate dust flows out of the slice}} - \overbrace{\underbrace{\underbrace{\underbrace{\underbrace{\underbrace{H\, W\, dL\ \alpha}_{\text{fiber volume}} \underbrace{\left(\frac{d_f\ L_f}{\frac{\pi d_f^2}{4}\ L_f}\right)}_{\text{collection area/ volume}}}_{\text{collection area}} \underbrace{\left(\frac{V_g}{(1-\alpha)}\right)}_{\text{gas velocity}}}_{\text{volume of gas swept/time}} \eta_T}_{\text{volume of gas swept clean/time}}\ C}_{\text{Mass of particles swept clean/time}}}^{\text{Rate dust accumulates in the slice}} \qquad (11)$$

Here,

V_g	is gas velocity into the filter, the superficial gas velocity
H	is filter height
W	is filter width
C	is dust concentration in the slice
α	is filter solidity, the fraction of filter volume made up of fibers
L_f	is fiber length
d_f	is fiber diameter
η_T	is total single fiber efficiency, the fiber collection efficiency due to all mechanisms

Equation (11) reduces to

$$\int_{C_{in}}^{C_{out}} \frac{dC}{C} = \int_{0}^{L} -\frac{4}{\pi}\left(\frac{\alpha}{1-\alpha}\right)\eta_T\ \frac{dL}{d_f} \qquad (12)$$

or

$$Pt = \frac{C_{out}}{C_{in}} = \exp\left[-\frac{4}{\pi}\left(\frac{\alpha}{1-\alpha}\right)\left(\frac{L}{d_f}\right)\eta_T \right] \ . \tag{13}$$

In terms of efficiency,

$$\eta = 1 - \exp\left[-\frac{4}{\pi}\left(\frac{\alpha}{1-\alpha}\right)\left(\frac{L}{d_f}\right)\eta_T \right] . \tag{14}$$

In Eq (14), note that η denotes the efficiency of the entire *filter* whereas η_T denotes the *single fiber efficiency* due to all mechanisms within the filter. These terms look similar, but carry different meanings.

Pressure Drop of a Media Filter

For a clean fiber mat, pressure drop, ΔP, is given by

$$\Delta P = \frac{16\ \mu\ \alpha\ V_g\ L}{Ku\ \ d_f^2} \tag{15}$$

where Ku is the Kuwabara number, given by Eq (2).

Characteristics of Used Media Filters

Filters are new only for the first instant they are used. The analysis presented above applies for clean beds of fibers. Once the fibers in a filter begin to collect particles, the flow field around the fibers will change, and cause a difference in collection efficiency and pressure drop. In general, the collection efficiency of media filters that collect solid particles increases over time because collected particles are often smaller than the fibers, so that these particles themselves become effective targets for subsequent particle collection. In contrast, the collection efficiency of media filters that collect liquid particles tends to decrease over time, particularly for particles small enough to collect by diffusion. Collected liquid can remain in the bed, held in place by surface tension. As a result the solidity of the bed increases, air velocity through the bed increases, and collection by diffusion decreases. Pete Raynor, a doctoral student in our lab, studied this phenomenon for his thesis. No effective methods are available to predict the efficiency of used filters.

Collected particles or droplets in a media filter will increase pressure drop. No effective methods are available to predict how pressure drop will change over time for these filters. Often, media filters are changed when their pressure drop increases to a value two or three times the value when the filter was new. Beyond that point, the extra cost of operating with high pressure drop may exceed the cost of installing a new filter, although the point of economic balance will vary greatly from application to application.

References

Davies, C.N., Air Filtration, Academic Press, London, 1973.

Lee, K.W. and R. Mukund, “Filter Collection”, in Aerosol Measurement, 2nd ed., P.A. Baron and K. Willeke, eds., Wiley, New York, 2001.

Hinds, W., Aerosol Technology, 2nd ed., Wiley, New York, 1999.