FIBROUS AEROSOL FILTERS

by
C. E. Lapple
Chemical Engineering Department
The Ohio State University
Columbus 10, Ohio

INTRODUCTION

There are, in general, two basic types of fibrous filters, the so-called "paper" or thin-bed filters and the deep-bed filters. The distinction between the two is primarily one of philosophy of application. The deep-bed filters are designed to be maintenance-free with a life corresponding to that of the entire installation or process. Once they become plugged with dust, the entire unit is abandoned. The paper filters, on the other hand, are usually designed for a limited life, to be replaced or cleaned periodically. They can, however, also be designed on an abandonment basis.

A discussion of deep-bed filters was presented at the Ames meeting in the Fall of 1952. These filters can be considered in two basic categories, the granular or sand types and the fibrous types. The discussion at that time dealt largely with the relative merits of these two types from the standpoint of design, performance, and cost. It was shown at that time that fibrous units possess a considerable economic advantage over sand filters although long-period large-scale experience was relatively meager for the fibrous type whereas the sand filters had an extended backlog of successful operation.

It is the purpose of the present paper to discuss the fundamental performance characteristics of fibrous filters. This discussion is essentially a preview of recent developments arising from regular thesis work at Ohio State University (12).

BASIC CONCEPTS

Methods of Expressing Collection Efficiency: While the collection efficiency of a filter is normally expressed as the fraction, η , of incoming aerosol particles that are collected in the filter, it is often more convenient to express collection efficiency in terms of number of transfer units, N_t, where the number of transfer units is related to the fractional collection efficiency by

$$\eta = 1 - e^{-N_t} \qquad (1)$$

or

$$N_t = \ln\left(\frac{1}{1-\eta}\right) \qquad (2)$$

It should be noted that the term N_t is identical to the corresponding term used in mass transfer for the case where there is a negligible vapor pressure of an absorbed gas or vapor from the liquid phase. It should also be noted that the term N_t is directly related to the decontamination factor, D.F., which has been widely used in atomic energy applications (1),

$$N_t = 2.303\ (D.F) \qquad (3)$$

The deposition of aerosol particles on body surfaces, such as cylinders or spheres, has been customarily expressed in terms of a target efficiency, η_t, defined as the ratio of cross sectional area of the original gas stream, from which particles of a given size are removed because the particle trajectory intersects the collecting surface, to the projected area of the collector in the nominal direction of flow.

For cases where the fibers are normal to the direction of flow, it is readily shown that

$$\eta_t = \pi \rho_b\ A\ N_t / s_v\ m \qquad (4)$$

In the derivation of Equation 4, it is assumed that η_t is a constant throughout the filter and either that the fractional deposition in any one layer of fibers is small or that there is complete mixing of the aerosol between layers. The first assumption restricts Equation 4 to homogeneous aerosols. For heterogeneous aerosols, however, Equation 4 will still express the performance characteristics for any given particle size if it is recognized that the terms N_t and η in Equation 1 will then represent the performance for that same size. If the fibers are not normal to the direction of flow, an additional orientation factor must be provided in Equation 4.

If means are availabile for evaluation η_t as a function of particle size, fiber size, and operating conditions, it is apparent that N_t may be calculated by means of Equation 4 and the corresponding values of η or D.F. from Equations 1 and 3, respectively. The subsequent discussion will show how η_t may be evaluated.

Deposition Mechanisms: The deposition of aerosol particles on a body may be due to any one or more of several mechanisms, where, as shown by numerous investigators, (2)(4)(5)(6)(7)(8)(9)(10)(11), the effectiveness of each mechanism is measurable in terms of the physical and operating conditions by a dimensionless group, which will be termed a separation number, N_s. These are listed below:

Deposition Mechanism	Separation Number
Flow-line (or Direct) Interception	$N_{sf} = D_p/D_b$
Inertial Interception	$N_{si} = k_m\ \rho_p\ D_p^2 u_o / 18\ \mu\ D_b$
Diffusional Deposition	$N_{sd} = D_v / u_o\ D_b$
Gravitational Deposition	$N_{sg} = u_t / u_o$
Electrostatic Deposition	
By Charges	$N_{sec} = k_m\ \epsilon_p\ \epsilon_{bs} / \mu\ \delta\ D_p\ u_o$
By Induction	$N_{sei} = k_m\ \epsilon_{bs}^2\ D_p^2\ (\delta_p - \delta) / \mu\ \delta^2\ D_b\ u_o$
Thermal	$N_{st} = [k/(2\ k + k_p)]\ [(T - T_b)/T]\ [\mu / k_m\ \rho\ D_b\ u_o]$

A detailed consideration will show that target efficiency is a function of some two dozen variables. By dimensional analysis, η_t may then be shown to be a function of some 1-1/2 dozen dimensionless groups, which include all of the N_s terms listed above in addition to other groups which measure modifying influences on the flow pattern and force fields.

For simplification, it may be assumed that electrostatic and thermal effects are negligible. The latter will normally be the case if no marked temperature gradients are present. The magnitude of electrostatic effects will be discussed later. With these assumptions it may be shown that

$$\eta_t = \psi(N_{sf}, N_{si}, N_{sd}, N_{sg}, N_{Re}, \epsilon_v) \qquad (5)$$

Relative to other deposition mechanisms, gravitational settling will normally be significant only with aerosol particles larger than about 1 micron diameter and with collecting bodies larger than some 100 microns diameter when operated at low face velocities. Gravity settling would be expected to act somewhat independently of the other mechanisms with little interactive effect. Consequently, for most purposes, this may be treated as a separate additive effect on target efficiency, having a magnitude on the order of N_{sg}.

To further simplify Equation 5 we may assume that the modifying influences of N_{Re} and ϵ_v on flow pattern are negligible. Equation 5 then becomes

$$\eta_t = \psi_1 (N_{sf}, N_{si}, N_{sd}) \qquad (6)$$

or, in alternate forms,

$$\eta_t = \psi_2 (N_{sf}, N_{sd}, N_{sc}) \qquad (7)$$

$$\eta_t = \psi_3 (N_{sf}, N_{si}, N_{sc}) \qquad (8)$$

where $$N_{sc} = N_{sf}^2/N_{si}\, N_{sd} = 18\, \mu/k_m\, \rho_p\, D_v \qquad (9)$$

The term N_{sc} is analogous to the Schmidt number in mass transfer and measures the interactive effect of flow-line and inertial interception and diffusional deposition. It should be noted that N_{sc} involves simply the physical properties of the gas and the aerosol particle.

In order to be able to predict that target efficiency from Equations 6,7 or 8, it is necessary to know the functional relationship between the variables. Several investigators have attempted to develop this relationship analytically for conditions where one or the other of the separating mechanisms is controlling. To date, however, no general solution has been developed. The nearest approach is that of Davies (2). The purpose of the investigation of Ohio State University was to develop the relationship experimentally.

EXPERIMENTAL PROCEDURE

In the experimental investigation, a test aerosol was passed through individual pads of fiber mats in series. Collection efficiencies were determined over a wide air velocity range (0.02 to 20 ft./sec.) by measuring the amount of aerosol retained in each pad and the amount passing the series of pads.

In order to take advantage of the convenience of colorimetric techniques, a dye was selected for producing the aerosol. The test aerosol was prepared from a volatile dye, du Pont "Oil Orange," in a large-scale version of the La Mer generator (3). Unlike the La Mer generator, however, the aerosol was formed by quenching the hot dye-vapor-laden air with filtered room air and no nucleation was employed. Throughout all the tests, the generator conditions were held constant to give a fixed reproducible aerosol as determined by frequent checks of filtration efficiency on a given filter-pad arrangement. The size of the aerosol particles was determined with jet impactors borrowed from the University of Illinois (8). The aerosol particles were relatively uniform but not homogeneous, having a mass median diameter of 0.4 micron and a standard geometric deviation of 1.4. It is believed that the particles were present in the air stream as spherical supercooled droplets of dye, although it is known that they crystallize into needles on shock or after a period of 10 to 20 minutes. Concentrations were on the order of 1 to 2 mg. of dye per cu.ft. of air.

The filter pads consisted of 0.1-in. thick layers of glass fiber packed between retaining screens. Five such pads were mounted in series in each test. Four types of fibers were used at various packing densities:

Fiber No.	Trade Name (Owens-Corning Fiberglas Corp.)	Mean Fiber Diameter, Microns
F-1	Aerocor-PF-Type AA	1.29
F-2	Basic 28	7.6
F-3	Fine Wool	10.7
F-4	Curly Wool (Type 115K)	29.4

All test fibers were fired at 400°C. to remove any binder or lubricant. The clean-up filters located after the test pads consisted of two standard Aerocor-PF-Type AA mats in series. The amounts of dye collected on each pad and by the clean-up filters were determined by leaching out the dye with benzene and analyzing the solutions colorimetrically.

EXPERIMENTAL RESULTS

Figure 1 shows the experimental results presented in the form of a plot of transfer units vs. superficial air velocity for the various fibers at several packing densities. It will be noted that the same type of curve was obtained with all the fibers and packing densities. The high-velocity end represents the region in which inertial interception is the controlling deposition mechanism. As the velocity is reduced, inertial deposition becomes less effective and collection efficiency (measured in terms of transfer units) decreases. At velocities on the order of 1 to 10 ft./sec., however, diffusional deposition becomes a significant factor. At lower velocities, diffusion becomes the controlling deposition mechanism and collection efficiency increases with a further decrease in velocity. It will also be observed that the curves become flatter for the fine fibers. This reflects the superimposed effect of flow-line interception, which is relatively more pronounced with the fine fibers and is independent of gas velocity in the magnitude of its effect.

While the data are presented directly in Figure 1, they are of little general utility in this form. It is necessary to generalize them in terms of fundamental concepts. This may be done by using the data as a means for evaluating the exact nature of the functional relationship implied by Equations 6, 7, and 8.

Since the gas properties and the aerosol particle size were held constant throughout this study, the value of the interaction parameter, N_{sc}, defined by Equation 9, was constant at a value of 2140. Equation 7 and 8 would now indicate, pursuant to the assumptions made in deriving them, that all the collection efficiency data expressed as target efficiencies, should be unique functions of either the inertial interception number, N_{si}, and the flow-line interception number, N_{sf}, or of the diffusional separation number, N_{sd}, and the flow-line interception number, N_{sf}. In other words, if the target efficiences obtained in this study are plotted against either N_{si} or N_{sd}, unique curves should be obtained for given values of N_{sf}.

In Figure 2, the data are shown in the form of a plot of target efficiency, η_t, vs. N_{si} with N_{sf} as the parameter. Figure 3 represents the same data plotted as target efficiency, η_t, vs. N_{sd} with N_{sf} as the parameter. It should be emphasized that these two figures are not independent; they are merely alternate ways of presenting the same data and it is possible to go from one to the other by direct calculation. Since the interaction parameter N_{sc} is constant, once any two of the three separation numbers, N_{sf}, N_{si}, and N_{sd}, are fixed, the third is determined (Equation 9). The value of the third parameter is shown as a dashed line in each figure. Figures 2 and 3 may be regarded as the graphical manifestation of the functional relationships implied by Equations 8 and 7, respectively, for the specific value for the interaction parameter of 2140.

DISCUSSION OF RESULTS

Validity of Assumptions: In deriving Equations 6, 7, and 8, several assumptions were made. The fact that the resulting indicated method of correlation did result in unique relationships for the data may be taken as evidence, although not proof, that the assumptions were valid within the precision of the data. Individual consideration of the various assumptions will lend further weight to this conclusion.

Since the tests were run under essentially isothermal conditions, no thermal deposition would be expected. Order-of-magnitude estimates also indicated that deposition by gravity settling should be negligible over the range of conditions employed. This was confirmed experimentally by the fact that no significant differences in collection efficiency were obtained when the gas was passed horizontally through the filter pads or vertically up or down through the pads.

It is known that the Reynolds number, N_{Re}, has an influence on the flow pattern around single cylinders and, hence, would be expected to influence deposition efficiency in that case. With proximate cylinders, as in fibrous filter pads, however, the Reynolds number should have no effect provided it is not above a value of on the order of 1. In the current tests the Reynolds number was less than 10 and usually less than 1. The absence of a Reynolds number effect on the flow pattern is further substantiated by the fact that the pressure drop through the pads was essentially a linear function of air velocity. For Reynolds numbers greater than 10, however, a distinct effect would be expected, although this region is beyond the scope of the present test data.

The data show no distinct effect of packing density on target efficiency although there is an indication that higher densities result in somewhat higher target efficiencies. Since bed densities were not varied widely, however, these indications are not sufficiently beyond the precision of the measurements to be conclusive. Actually it would be expected that higher bed densities would compress the streamlines around the fibers and yield higher target efficiencies. For the range of densities investigated, however, it may be concluded that density has no major effect on target efficiency.

From the fact that a correlation was obtained by neglecting electrostatic effects, one might conclude that electrostatic effects were of no major significance in these tests. If the electrostatic separation number followed the same trend in all the tests as one of the other separation numbers, however, this conclusion would not be valid. An examination of the various separation numbers will show that the group N_{sei}, which is a measure of electrostatic deposition by induction, would be directly proportional to the diffusional separation number, N_{sd}, if any surface charge, ϵ_{bs}, had been the same on all the pads tested. While this would represent a coincidental condition, it is not an unlikely one. The only direct evidence against this possibility is the fact that the target efficiencies obtained are of the order of magnitude that would be expected if diffusion were a controlling factor in the absence of inductive deposition. Consequently, while it cannot be conclusively demonstrated that electrostatic effects were absent, it can be concluded that any such effects that might have been present were not major factors.

Comparison with Other Investigators: There are only two sets of data available in the literature which are sufficiently complete to approach a basis for comparison. The data of Blasewitz et al (1) dealt with an aerosol that was quite heterogeneous and, in addition, involved considerable uncertainty as to the magnitude of the particle size. La Mer et al (3), while complete in other respects, did not measure the properties of the filter pads. Hence, the comparative interpretation of their data involves a possible error of several-fold. When presented on the same basis as Figures 2 and 3, the data of Blasewitz and La Mer indicate qualitative agreement with the present data.

The data in Figures 2 and 3 suggest limiting curves for $N_{sf} = 0$. These have been drawn in as dotted or short-dashed lines. In Figure 2 this limiting curve would represent the target efficiency at low Reynolds numbers if enertial interception alone were involved. Langmuir (4) reports a calculated value of N_{si} of 0.27 below which no deposition by inertial interception can occur at low Reynolds numbers, although he gives no details as to the method of arriving at this value. This value was used as an asymptote in drawing the limiting curve for $N_{sf} = 0$ in Figure 2. Also shown as a dotted curve in Figure 2 are the calculated values reported by Langmuir and Blodgett (5) for potential flow. These values would correspond to the target efficiencies to be expected for pure inertial interception at very high Reynolds numbers and should be much greater than those for viscous flow.

Davies (2), Langmuir (4), Lewis and Smith (6), Ranz (7), and Stairmand (11) have all developed approximate analytical expressions for target efficiencies under conditions of pure diffusion to single cylinders. While these expressions differ by several-fold factors owing to differences in simplifying assumptions, that of Langmuir is probably the most accurate. Languir's expression falls below the dotted line of Figure 3 by a factor ranging from 0.5-to 3-fold. Lewis and Smith obtain results 70% higher than the dotted line while Stairmand is higher by a factor of 3. Ranz is in approximate agreement with Langmuir. It should be remembered that these analytical expressions are for single cylinders. Higher target efficiencies would be expected for proximate cylinders.

APPLICATION

Figures 2 and 3 give a quantitative representation of deposition in fibrous filter media at low Reynolds numbers (less than 10) in the absence of significant thermal, electrostatic, or gravitational effects. They are specific, however, for an interaction number of 2140. To obtain a generalization of these curves, it would be necessary to obtain similar curves for a range of the interaction number. For higher values of the interaction number, the curves of constant N_{sf} would, in general lie below those of Figures 2 and 3; while, for lower values of N_{sc}, the curves of constant N_{sf} would lie above those of Figures 2 and 3. In either case, however, the curves of constant N_{sf} would approach those of Figures 2 and 3 at high values of N_{sd} or N_{si} (i.e. at the right-hand side of each figure). In other words, for high values of N_{si} and N_{sd}, the curves of Figures 2 and 3 would be sensibly independent of N_{sc}.

To use Figures 2 and 3 for general design estimates in the absence of more extensive similar data at other values of the interaction number, the following procedure is suggested. For the specific values of the separation numbers N_{sf}, N_{si}, and N_{sd} involved in a particular problem, calculate from Figures 2 and 3 the target efficiency corresponding to each of the three combinations of two of the separation numbers. In general, this will yield three values for the estimated target efficiency. For the singular case where the interaction number for the specific problem is 2140, these three values of target efficiency will, of necessity, come out equal. If the interaction number is less than 2140, use the highest of the three target efficiency values obtained. If the interaction number is greater than 2140, use the lowest of the three target efficiencies obtained. This approximation should yield estimates that are correct within a factor of two for the range of conditions likely to be of practical interest.

SUMMARY AND CONCLUSIONS

A method has been presented for generalizing the principles governing deposition of aerosol particles in fibrous packing by the mechanisms of flow-line interception, inertial interception, and diffusional deposition. Experimental data have been obtained which express these principles quantitatively for an interaction number of 2140. In the absence of more extensive data over a range of interaction numbers, a method is suggested for utilizing the present data for general design or performance estimates.

The following is a list of indicated directions for further research to fully develop the fundamentals of aerosol deposition in filters:

1. Confirming Data. In this field, with its many uncertainties regarding basic techniques of measurement, it is especially desirable to obtain comparisons with other data obtained independently and preferably using different techniques. Literature data currently available are not sufficiently complete to enable quantitative comparisons to be made.

2. Effect of Interaction Number. While an approximate method is suggested for employing the data presented herein for general design, it is necessary that further data be obtained over a wide range of the interaction number (say for N_{sc} ranging from 100 to 100,000).

3. Effect of Bed Density. Data are required to establish the quantitative effects of packing density. The present study involved a relatively limited range. Such data should be extended to dense packings such as may be encountered in compressed mats.

4. Effect of Reynolds Number. For practical conditions under which deposition by flow-line interception or diffusion are significant, the Reynolds number should be sufficiently low that it is questionable whether the Reynolds number would have any significant separate influence. For inertial interception, however, high values of the Reynolds number, for which marked effects would be expected, are frequently encountered.

5. Effect of Mean Free Path of Gas Molecules. Insofar as the mean free path effects the flow around fibers, this factor has been essentially ignored by all but Langmuir (4) who provides an approximate allowance. In practice it will be significant with very fine fibers or at reduced pressures. Although not separately allowed for, it was probably beginning to be a significant factor in the case of the finest fiber employed in the present study.

6. Effect of Other Deposition Mechanisms. Considerable work remains to be done to evaluate the principles of deposition by gravity, electrostatic, and thermal mechanisms. Ranz (7) (9), in particular, has made a start in this direction.

7. Effect of Fiber Orientation. There has been essentially no systematic work on the quantitative effect of fiber orientation. The present study dealt exclusively with fibers mounted perpendicular to the gas flow.

8. Deposition in Granular Solids. There has been essentially no fundamental work to evaluate the quantitative principles of deposition in beds of granular solids.

9. Filter Life. The above-indicated needs for further research are aimed primarily at developing the fundamentals of deposition. In practice, a far more important consideration is that of filter life from the standpoint of plugging by the particles deposited in the filter. To date there has been no systematic evaluation of this phase. Actually, before a truly fundamental analysis of filter life can be made, it will probably be necessary to first develop the principles of deposition.

10. Mechanical Stability. In practice, the compressive properties of fibers are an important consideration in design of deep-bed filters. Mechanical stability with time under corrosive or stressed conditions is also very important. These phases have hardly been touched upon in investigations to date.

NOMENCLATURE

A = face area of filter pad normal to direction of gas flow, sq. cm.

D_b = fiber diameter, cm.

D_p = aerosol particle diameter, cm.

D_v = diffusion coefficient for aerosol particle = $k_m R T / 3 \pi \mu N D_p$, sq. cm./sec.

k = thermal conductivity of gas, (cal.)/(cm.)(°K.)(sec.)

k_m = Stokes-Cunningham correction factor for mean free path of gas molecules, dimensionless.

k_p = thermal conductivity of aerosol particle, (cal.)/(cm.)(°K.)(sec.)

m = mass of filter pad through which gas flows, grams.

N = Avagodro"s number = 6.023×10^{23} molecules/(gram mole).

N_{Re} = Reynolds number = $D_b\, u_o\, \rho/\mu$, dimensionless.

N_s = separation number, dimensionless.

N_{sc} = interaction number = $18\,\mu/k_m\, \rho_p\, D_v$, dimensionless.

N_{sd} = diffusional separation number = $D_v/u_o\, D_b$, dimensionless.

N_{sec} = electrostatic separation number for effect of charges = $k_m\, \epsilon_p \epsilon_{bs}/\mu\, \delta\, D_p\, u_o$, dimensionless.

N_{sei} = electrostatic separation number for effect of induction = $k_m \epsilon_{bs}^2\, D_p^2\, (\delta_p - \delta)/\mu\, \delta^2\, D_b\, u_o$, dimensionless.

N_{sf} = flow-line interception number = D_p/D_b, dimensionless.

N_{sg} = gravity separation number = u_t/u_o, dimensionless.

N_{si} = inertial interception number = $k_m\, \rho_p\, D_p^2\, u_o/18\,\mu\, D_b$, dimensionless.

N_{st} = thermal separation number = $[k/(2\,k + k_p)]\,[(T - T_b)/T]\,[\mu/k_m\, \rho\, D_b\, u_o]$, dimensionless.

N_t = number of transfer units, dimensionless.

R = gas constant, 8.31×10^7 (ergs)/(°K.)(gram mole).

s_v = specific surface of fibers, = $4/D_b$ for cylindrical fibers, sq. cm./cu. cm.

T = gas temperature, °K or °C abs.

u_o = superficial gas velocity (based on filter face area), cm./sec.

u_t = terminal settling velocity of aerosol particle in gravity field, cm./sec.

δ = permittivity of gas, (statcoulombs)^2/(dyne)(sq. cm.).

δ_p = permittivity of aerosol particle, (statcoulombs)^2/(dyne)(sq. cm.).

ρ_b = fiber density, g./cu. cm.

ρ_p = aerosol particle density, g./cu. cm.

μ = gas viscosity, poises.

ϵ_v = fractional voids in filter pad, dimensionless.

ϵ_p = electric charge on particle, statcoulombs.

ϵ_{bs} = electric charge on fiber surface, (statcoulombs)/(sq. cm.).

η = overall fractional collection efficiency, fraction of particles entering filter that are deposited in the filter pad, dimensionless.

η_t = ratio of cross-sectional area of the original aerosol stream, from which particles of a given size are removed because the particle trajectories intersect the fiber surface, to the area of the fibers projected normal to the nominal direction of gas flow, dimensionless.

ψ = "a function of."

REFERENCES

1. Blasewitz, A. G., et al, General Electric Company, Hanford Works, Document H W 20847, April 16, 1951.
2. Davies, C. N., Proc. Instn. Mech. Engrs. (London), 1 B, 185-213 (1952); Ninth International Congress on Industrial Medicine (London), pp. 1-36, Sept. 13-17, 1948.
3. La Mer, V. K., et al, Report N Y O-512, Contract No. A T - (30-1) - 651, 1951.
4. Langmuir, I., O.S.R.D. Report No. 865, Part IV, Sept. 4, 1942.
5. Langmuir, I., Blodgett, K. B., Report No. RL-225, General Electric Research Laboratory, Schenectady, N. Y., 1944-45.
6. Lewis, W. K., Smith, J. M., O.S.R.D. Report No. 1251, Dec. 15, 1942.
7. Ranz, W. E., Univ. of Ill., Eng. Exp. Station, Technical Report No. 3, SO-1004, March 31, 1951.
8. Ranz, W. E., and Wong, J. B., Archiv. Ind. Hyg. and Occupational Medicine, 5, 464-77 (1952); Ind. Eng. Chem., 44, 1371-81 (1952).
9. Saxton, R. L., Ranz, W. E., Univ. of Ill., Eng. Exp. Station, Technical Report No. 6, SO-1007, Dec. 31, 1951; J. Appl. Physics, 23, 917-23 (1952).
10. Sell, W., Forsch. Gebiete Ingenieurw., 2, Forschungsheft No. 347, Aug., 1931.
11. Stairmand, C. J., Trans. Instn. Chem. Engrs. (London), 28, 130-137 (1950).
12. Thomas, D. G., "Deposition of Aerosol Particles in Fibrous Packing," Ph.D. Thesis, Ohio State University, 1953.

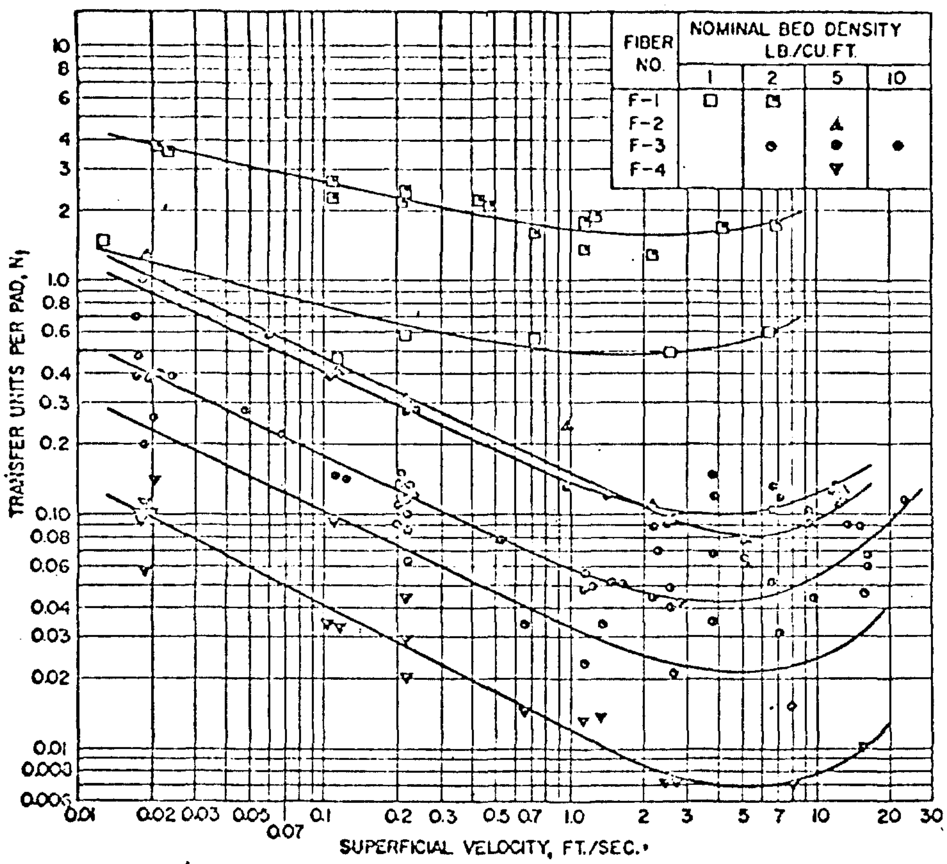

FIG. 1

SUMMARY OF EXPERIMENTAL COLLECTION EFFICIENCY DATA

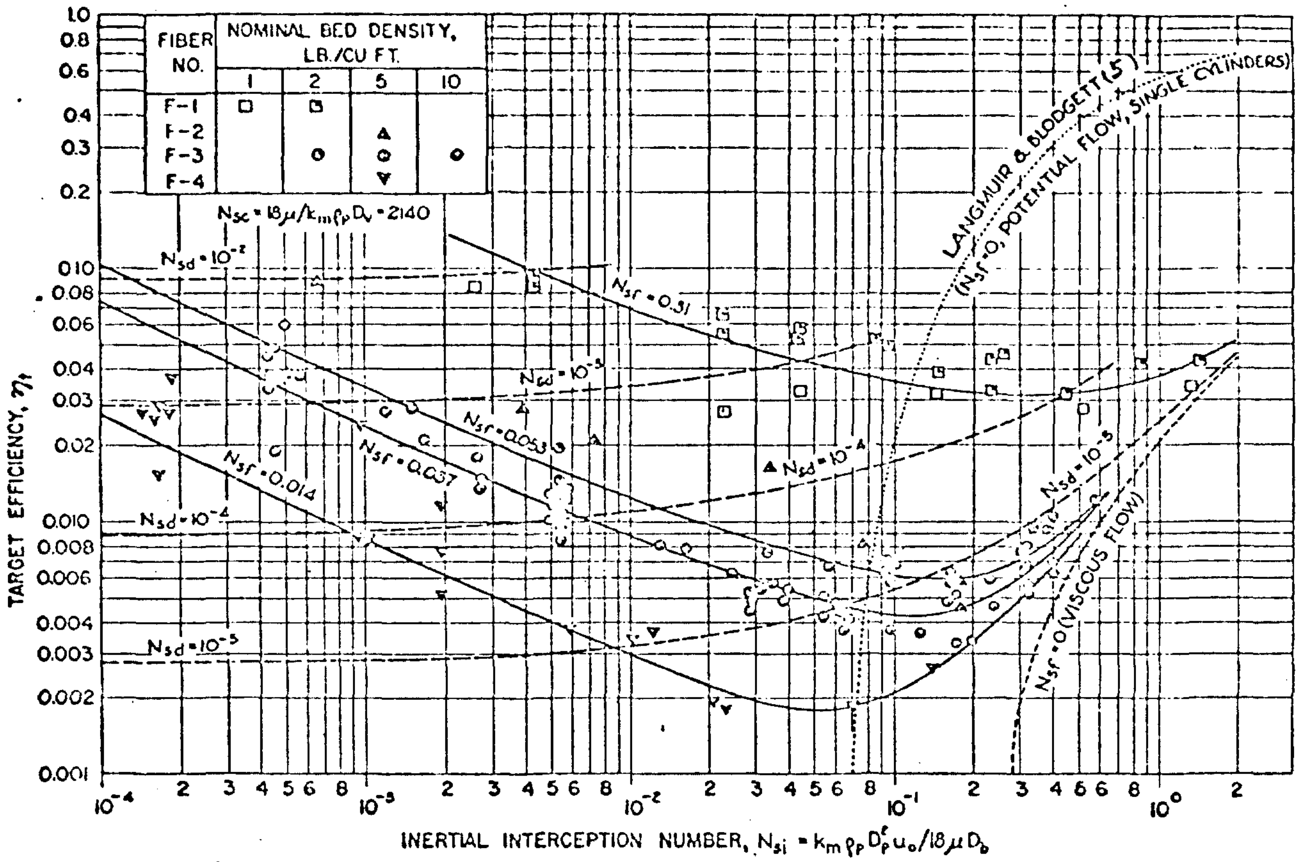

FIG. 2

TARGET EFFICIENCY AS A FUNCTION OF THE INERTIAL INTERCEPTION NUMBER

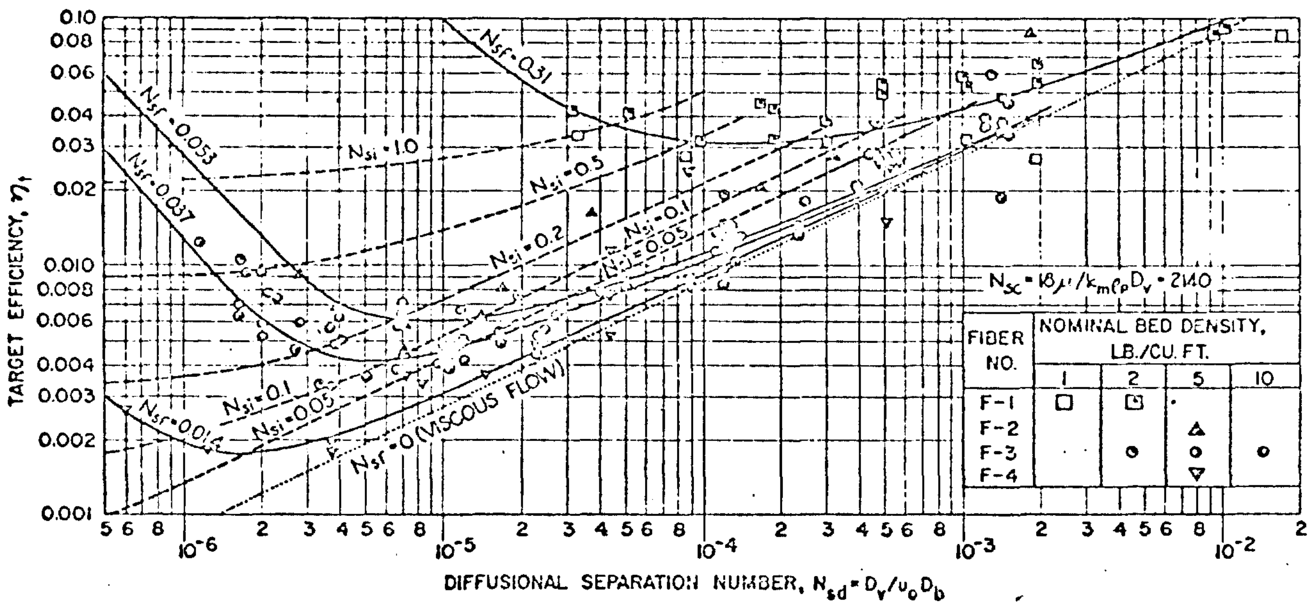

FIG. 3

TARGET EFFICIENCY AS A FUNCTION OF THE DIFFUSIONAL SEPARATION NUMBER