ENGINEERING RESEARCH INSTITUTE
UNIVERSITY OF MICHIGAN
ANN ARBOR

Interim Technical Report No. 3

THE PERFORMANCE OF PACKED SECTIONS IN OIL-BATH AIR CLEANERS

Seymour Calvert

Project 2233-14-T

DETROIT ARSENAL, DEPARTMENT OF THE ARMY
CONTRACT NO. DA-20-089-ORD-36962
CENTER LINE, MICHIGAN

May 1955

TABLE OF CONTENTS

	Page
LIST OF TABLES	iii
LIST OF FIGURES	iv
SUMMARY	v
INTRODUCTION	1
DUST-COLLECTION EFFICIENCY	2
Experimental Work	6
Experimental Data	10
Prediction of Efficiency for the Experimental Conditions	10
Discussion of Results	17
Conclusion	23
PRESSURE DROP FOR AIR FLOW THROUGH FIBROUS PACKING	24
Pressure Drop for Beds of Cylindrical Fibers	24
Experimental Work	28
FLOODING POINTS IN FIBROUS PACKING	30
Mechanism of Flooding	36
REFERENCES	37

LIST OF TABLES

		Page
1.	Predicted Collection Efficiency for the Packed Section of a Donaldson Company No. A-14111 Oil-Bath Air Cleaner	4
2.	Predicted Collection Efficiency for Various Particle Sizes in Each of the Packed Stages of a Donaldson Company No. A-14111 Oil-Bath Cleaner	5
3.	Particle Size Distribution for 0- to 3- Micron Vapor-Blast Silica	7
4.	Data for Dust-Collection Efficiency Runs	11
5.	Dimensions of Packing Materials	16
6.	Sample Calculation of Collection Efficiency for a 0.75-inch Deep Bed of Wire Mesh	22
7.	Comparison of Predicted and Experimental Collection Efficiencies	22
8.	Comparison of Predicted and Experimental Pressure Drops for the Flow of Air (Air Velocity is 20 ft/min for All Cases)	28
9.	Values of Parameters for Experimental Packings	31

LIST OF FIGURES

No.		Page
1.	Predicted and experimental impaction efficiencies for collectors of various shapes.	3
2.	Schematic drawing of collection-efficiency apparatus.	8
3.	Dust feeder.	9
4.	Array of collector wires.	13
5.	Predicted collection efficiency for 0.0125-inch-diameter wire grids, assuming complete mixing.	18
6.	Predicted collection efficiency for 0.0125-inch-diameter wire, 12 grids, assuming no mixing.	19
7.	Predicted dust penetration for 0.006-inch-diameter wire mesh.	20
8.	Predicted dust penetration for 0.006-inch-diameter wire mesh.	21
9.	Drag coefficient vs Reynold's number.	27
10.	Predicted pressure drop group vs air velocity for air flow through beds of round steel wire.	29
11.	Flooding points for 0.00528-inch-diameter, No. 3 steel wool (air and SAE No. 10 oil).	32
12.	Flooding points for 0.0125-inch-diameter wire grid (air and lube oil).	33
13.	Flooding-point correlation.	34
14.	Flooding-point correlation for fibrous packing.	35

SUMMARY

The study of the performance of fibrous packing was undertaken as a part of an engineering investigation of oil-bath air cleaners.

The interim technical report is written at a stage in the research program when sufficient data are at hand to permit a meaningful interpretation. Individual aspects of the study are not necessarily complete and where they are not, the need for further study is indicated.

Experimental and analytical results indicate the following:

1. Dust-collection efficiency for beds of fibrous materials can be predicted within a few-percent accuracy through the employment of "target efficiency" data for single collector elements. This method takes into account the size and physical properties of the dust, the velocity, and physical properties of the suspending fluid, and the size and packing arrangement of the fibers.

2. Pressure drop for the flow of fluids through beds of fibrous materials may be adequately predicted by a method based on the drag relationships for single elements when the average space between fibers is greater than about 8 fiber diameters. Denser packings give higher pressure drops than predicted by this method due to the increase of drag coefficient as spacing is decreased. This effect remains to be studied. An empirical correlation for pressure drop in beds of steel wool was developed from the data on the flow of air through steel wool.

3. Flooding-point data for the system air and lube oil in fibrous packing are fitted satisfactorily by an empirical correlation of Sherwood, et al.[6] The relationship between flooding point and liquid holdup remains to be established.

INTRODUCTION

One aspect of the general investigation of engine air cleaners is the analysis of the function of fibrous packing elements such as screens, wire mesh, and steel wool. Such elements are employed in oil-bath air cleaners as the final cleaning stage, usually following an impingement section. The packing serves as a collection element for both the dust which is too fine to be captured by the impingement section and the oil drops which are blown out of the impingement section.

The major point of interest concerns the mechanism by which fibrous elements collect dust and the possibility of predicting collection efficiency. In a previous report[2] it was proposed that collection by impingement seemed the most likely mechanism and presented a method for computing the collection efficiency for fibers. Following that, there remained the task of obtaining experimental verification of the theoretical analysis. Consequently, an experimental investigation of dust collection efficiency was initiated. Several months after this, a paper concerning an investigation of the collection efficiency of metal wool fibers was presented; and the data established the validity of the theoretical method of prediction. As a result of this good fortune, it was not necessary to continue with as extensive a program as originally planned, although it seemed advisable to get some limited data on the collection efficiency of round wires and to evaluate the effect of mixing in the air stream within the bed.

Another significant point of interest concerns the function of fibrous packing as an oil entrainment separator. It very quickly becomes apparent that the problem here is not one of capturing the oil drops, since this is easily done, but rather of preventing the re-entrainment of drops due to the flooding of the packing. This phenomenon is seen as "oil carry-over" in air-cleaner operation and it is this which dictates the upper limit of air-cleaner capacity. Consequently, the determination of flooding points was included in the experimental program. Also included in the experimental program was the study of pressure drop for air flow through fiber beds.

This report covers the work done to date on the evaluation of the functions of the packed section of an oil-bath air cleaner. The complete air cleaner includes an impingement or turning baffle section followed by one or more packed sections. The two sections are considered as separate elements of a composite and for the most part have been studied independently. Thus, the experimental data on the behavior of packing materials have been obtained from the operation of packed columns which did not include an impingement section.

The major functions of the packed section are to collect dust which has escaped the impingement zone and to prevent the carry-over of oil. The oil, which is blown into the packing from the impingement section, washes the packing fibers clean and acts as an adhesive for the retention of dust.

It was the purpose of this study to gain an understanding of these functions and to develop methods for predicting the performance of fibrous packing materials. Specifically, the study has been concerned with the following topics:

1. dust-collection efficiency of fibrous packing,
2. pressure drop for air flow through fibrous packing, and
3. flooding points for air and oil flow through fibrous packing.

DUST-COLLECTION EFFICIENCY

A preliminary study of the literature on the subject of aerosol collection resulted in the belief that the principal mechanism of collection in an oil-bath air cleaner is by impaction. In other words, The principal force causing the separation of a dust particle from the air stream is inertia. The behavior of particles subjected to inertial forces when an air stream passes around solid objects has been studied by several investigators and the equations describing the particle trajectories have been solved. These data on particle trajectories have been interpreted in terms of collection efficiency and this interpretation is presented in graphical form.[4]

A plot of collection efficiency versus the collection parameter is shown in Fig. 1. This plot shows the fraction of the particles originally traveling toward the target which will strike it. It can be seen that the collection efficiency depends on the particle size and density, the gas velocity and viscosity, and the collection diameter. Efficiency increases with increasing particle size and gas velocity, and decreases with increasing collector size.

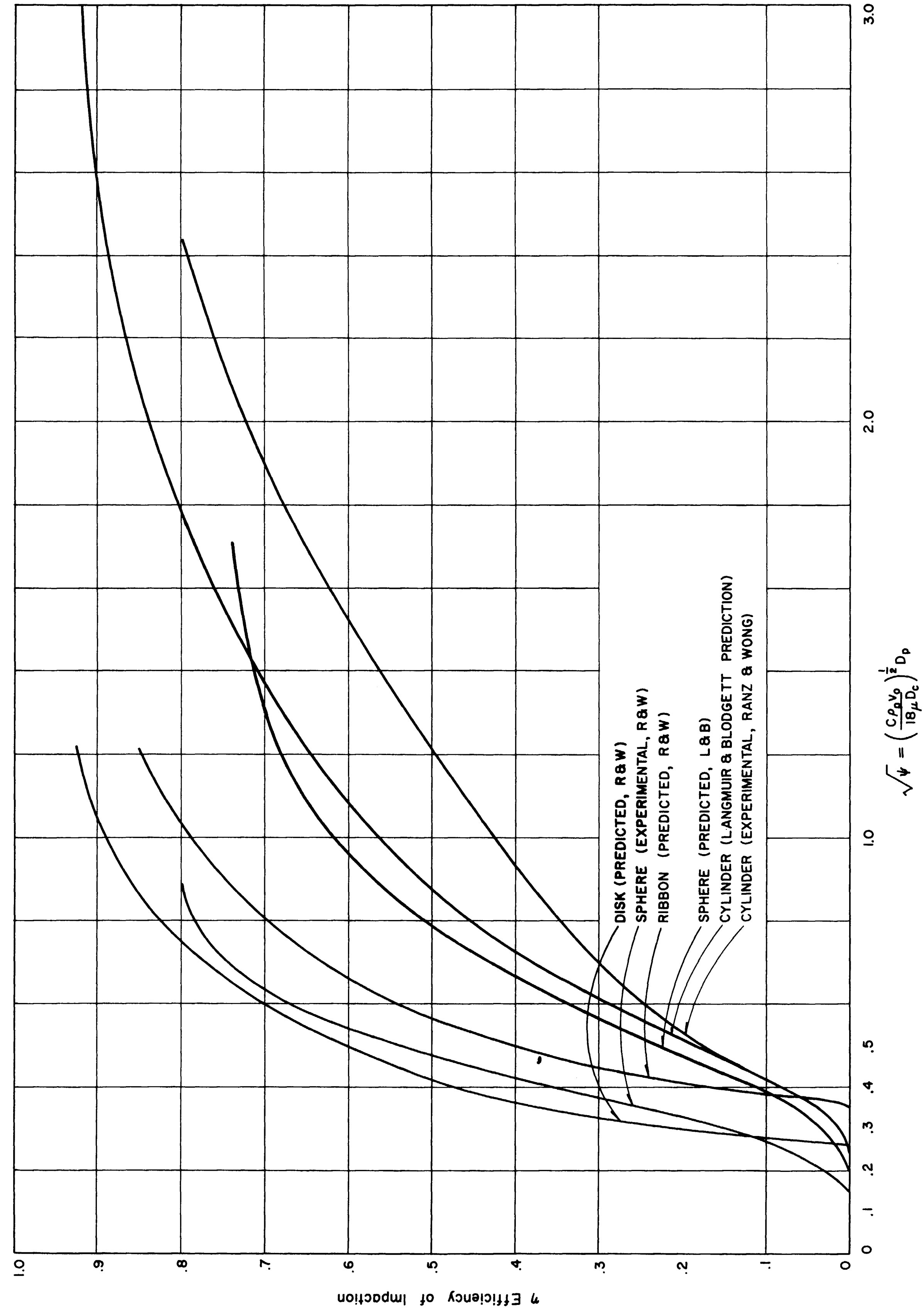


Fig. 1. Predicted and experimental impaction efficiencies for collectors of various shapes.[4]

One method by which this information may be applied to the prediction of packed-section collection efficiency has been fully described in Interim Technical Report No. 1.[2] An illustrative example was given for a section of screen packing similar to the lower element in a production-model of a Donaldson oil-bath air cleaner such as is presently used on tank engines. The efficiency prediction has been worked out in more detail since then and the results are given in Table I.

TABLE I

PREDICTED COLLECTION EFFICIENCY FOR THE PACKED SECTION OF A DONALDSON COMPANY NO. A-14111 OIL-BATH AIR CLEANER

Stage	Component	Air Velocity, ft/sec	Fine Dust Collection Efficiency of Air Cleaner, %
1	Removable element, 7 layers of 14-mesh screen, 0.0165" wire diameter.	50	86.9
		25*	80.4
		16.7	76.5
		12.5	74.2
2	First fixed element, 12 layers of crimped 8-mesh hardware cloth, 0.015" wire diameter.	12.5*	88.7**
3	Final fixed element, 26 turns of crimped 12-mesh screen, 3" deep, 0.0105" wire diameter	12.5*	90.66**

* Velocity at rated capacity

** Cumulative efficiency, including that of previous stage(s) at rated capacity.

The data in Table I show the effect of air velocity on collection efficiency in the first stage, as well as the decreasing contribution to efficiency made by the following stages. It is interesting to note that while an increase in velocity from 25 to 50 feet per second in Stage 1 gives almost as great an increase in efficiency as does the addition of Stage 2 at rated velocities, it is not accomplished in the same way. The increase in velocity results in a higher collection efficiency for small particles, while the increase in bed depth, even though at a lower velocity, results in a greater total collection efficiency for particles larger than the minimum size. This is indicated by the predicted efficiencies for various particle sizes, as given in Table II.

TABLE II

PREDICTED COLLECTION EFFICIENCY FOR VARIOUS PARTICLE SIZES IN EACH OF THE PACKED STAGES OF A DONALDSON COMPANY NO. A-14111 OIL-BATH CLEANER

Particle Dia, micron	Collection Efficiency, %			
	Stage 1 25'/sec	Stage 1 50'/sec	Stage 2 12.5'/sec	Stage 3 12.5'/sec
1	16.0	56.6	0	8.4
2	63.0	75.5	71.2	23.6
3	77.4	86.8	73.6	48.5
4	85.3	91.8	81.0	65.5
5	90.0	94.2	88.4	79.0
6	92.7	95.3	91.9	88.0
7	94.1	95.9	94.1	
8	95.0		95.4	93.0
9	96.8		96.3	
10	97.0		96.8	95.0

Note: These predictions are based on Ranz and Wong's[4] experimental data and on the assumption that mixing is complete.

In general, it can be seen that the theoretical method of efficiency prediction is quite informative and is certainly of value in pointing out the relative merit of various types of packing and the effect of air velocity. The accuracy of the predictions has been validated by several experimental studies on the collection of liquid drops on single collectors although at the time this program began there were no experimental data on the collection of solid particles by multiple elements. Although there seemed to be little doubt that solid particles would behave in the same fashion as liquid drops, the relationship between the behavior of single collector elements and groups of elements had not been established nor was the effect of the scrubbing liquid known.

An experimental program for the study of fluid-flow characteristics and collection efficiency of fibrous packed sections was initiated. At the time when the pressure-drop and flooding-point runs on various sizes of steel wool had been completed and collection-efficiency tests were beginning, a paper on the collection efficiency of water-washed metal wool was presented by R. G. Calkins.[1] That investigation involved the experimental determination of collection efficiency for two different grades of metal wool and three different types of dust. The data showed that the collection efficiency can be predicted with an average error of about 2% (high) and a maximum of 5% (high). It was found that the flowrate of the scrubbing liquid (water) had little or no effect on the collection efficiency so long as there was sufficient flow to wash the fibers clean.

This information was quite helpful, although there remained one point which was not completely settled. That was the relationship between the behavior of a single collector wire and the behavior of a group of wires. While Calkins' data can yield an answer on this point, it is only a partial answer since he made experimental determinations with fibers which had a triangular cross section and based his predictions on cylindrical collectors with an "equivalent diameter." Consequently, our experimental program was directed toward the investigation of beds of cylindrical wires so that the effect of irregular collector cross section would be eliminated.

EXPERIMENTAL WORK

Dust-collection efficiency was determined for two types of packing material with air flowrates near and below the flooding point, and with countercurrent flow of either SAE No. 30 or SAE No. 10 oil. One type of packing consisted of a stack of 3-1/4-inch-ID rings, to which 0.0125-inch-diameter copper wires were soldered in parallel rows 1/8 inch apart on centers. The rings were arranged so that alternate layers of wire oriented at right angles in the horizontal plane and so that the majority of the wires did not lie in the same vertical plane as the wires above or below them. The resulting bed consisted of a cylindrical section 3-1/4 inch-ID and filled with 12 layers of wire which were 0.075 inch apart in the vertical direction (direction of air flow).

The other type of packing was knitted, steel wire mesh which was crimped on a 45-degree angle to the length of the strip. The wire diameter was 0.006 inch, the metal density was 7.6 gm/cc, the bed density was 0.127 gm/cc, and the porosity of the bed was 0.9833. The bed was made by winding a strip of the mesh in a spiral until a 3-3/4-inch-OD roll was obtained. The bed depth was varied by folding the strip of mesh to the proper width before rolling it.

The bed was placed inside a 2-foot-long column of 3-3/4-inch-ID lucite tubing so that the bottom of the bed was 18 inches above the bottom of the column. Air was introduced through a 2-inch-ID tube cemented in the side of the column with its center 2 inches above the bottom of the column. The air outlet was a similar tube located with its center 2 inches below the top of the column. Dust was introduced into the air-inlet tube through a 3/4-inch-ID tube located with its center 1 inch from the inside of the column. Figure 2 shows the apparatus used for the packed-column collection-efficiency tests.

The test dust used in all the collection-efficiency tests was "0- to 3- micron" silica prepared by the Vapor Blast Manufacturing Company. The particle size distribution for this dust was determined by Mr. Beckett of the Fram Corporation by means of a centrifugal sedimentation technique (the Pillsbury Analyzer) and is given in Table III.

TABLE III

PARTICLE SIZE DISTRIBUTION FOR 0- TO 3- MICRON VAPOR-BLAST SILICA

Size Range, micron	Weight % in Size Range	Cumulative % Smaller than Maximum Size in Range
30+	0.6	99.9
25-30	0.7	99.3
20-25	0.7	98.6
15-20	10.9	97.9
9-15	35.1	87.0
5- 9	35.2	51.9
2.5- 5	12.2	16.7
1.0- 2.5	3.2	4.5
0- 1	1.3	1.3

The dust feeder used in these tests was a type designed by us and is illustrated in Figure 3. It is comprised of an air-jet ejector, a dust reservoir tube, and an air-inlet tube. The air-jet ejector pumps dustladen air from the reservoir tube and causes the flow of air to enter the reservoir through the inlet tube. The tip of the inlet tube is set above the just level and is curved so that the air enters the reservoir tube tangentially and causes a rotating motion of air within the reservoir. Dust is "eroded" from the surface of the dust layer by the rotating air stream and is carried up the reservoir tube to the ejector. The inlet to the ejector is also tangential to the ejector body so a rotating motion is set up within the ejector. It can be seen that the rotation which occurs in both the reservoir tube and the ejector tends to classify the dust and causes large particles and agglomerates to roll around the surface of the container until they are

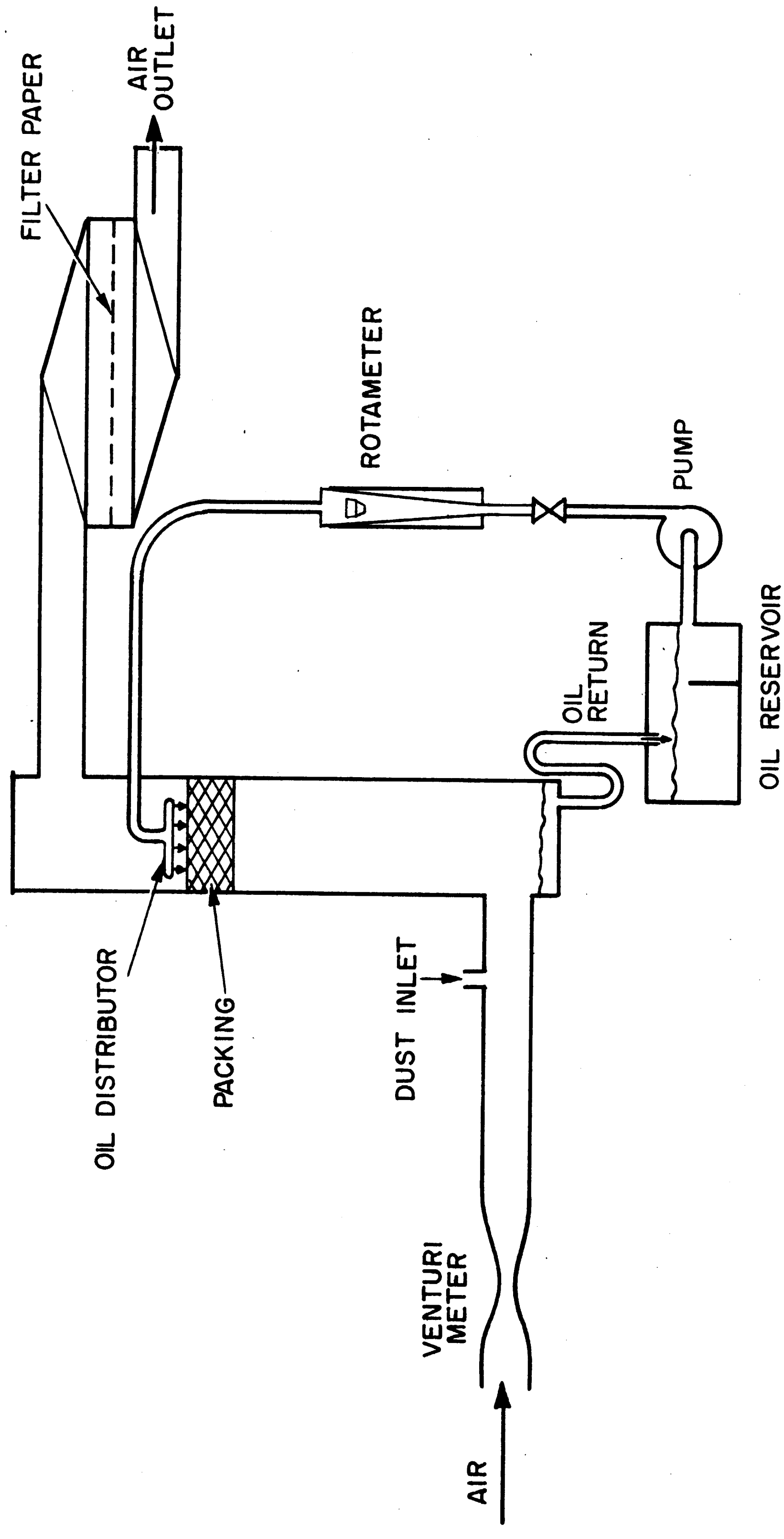


Fig. 2. Schematic drawing of collection-efficiency apparatus.

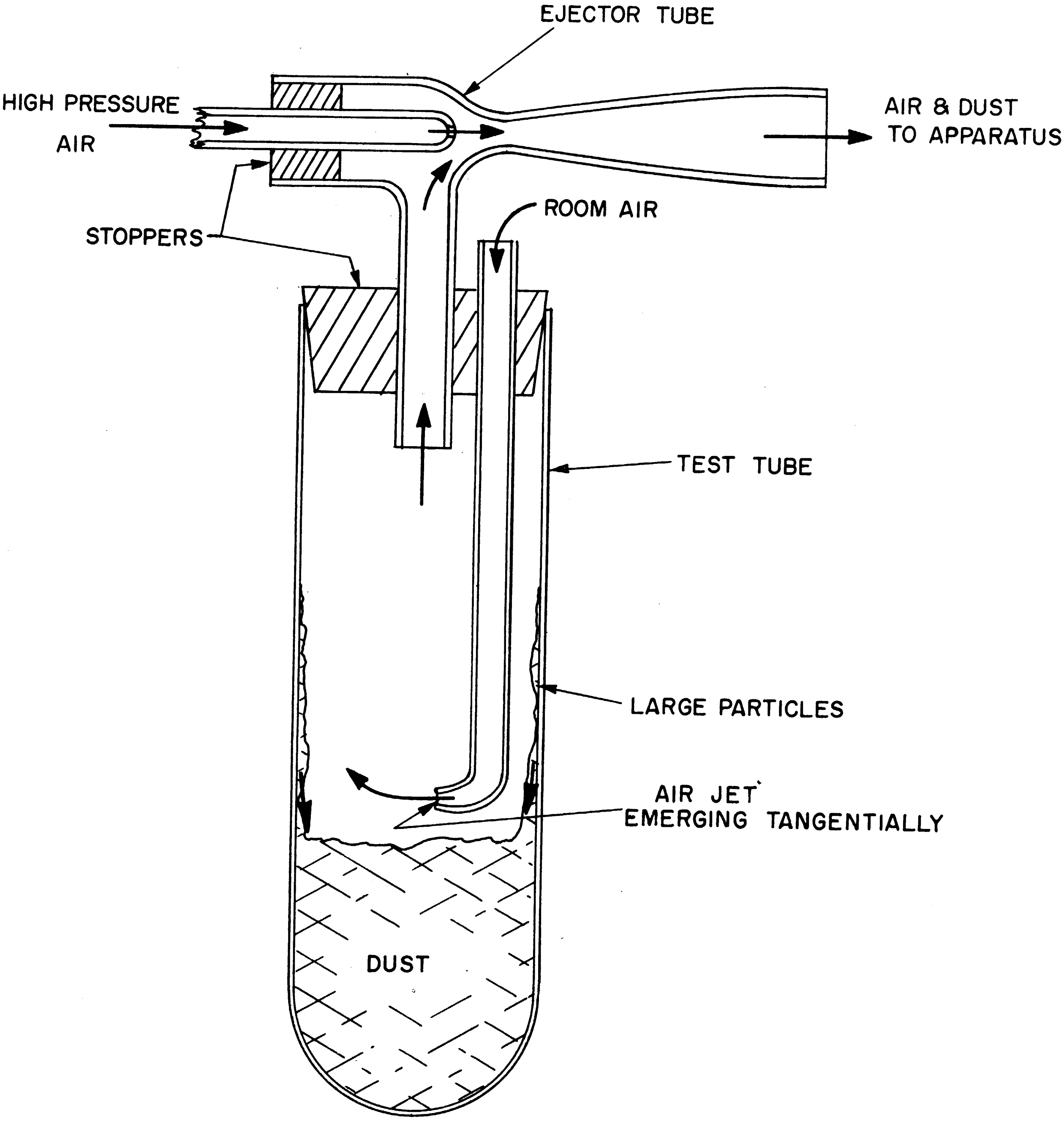


Fig. 3. Dust feeder.

re-entrained. This action, as well as the impingement by the sonic-velocity air jet in the ejector, is intended to break up agglomerates. The evaluation of this type of feeder was not completed, although preliminary tests indicated that the dust was fairly well dispersed.

The dust which passed through the test section was filtered out of the air stream by means of a 15- x 15-inch sheet of Mine Safety Appliance Company No. 1106-B paper. The quantity of dust collected was determined by weighing the filter paper before and after each run. Test strips of MSA paper were placed in the filter holder downstream from the filter paper in order to determine the moisture pickup or loss, but this proved to be negligible. Because the tests were run close to flooding conditions for the packing, it was necessary to place an oil disengagement section in front of the filter. This section consisted of a 5-inch-diameter, 8-inch-long cylindrical chamber with the air inlet and outlet tubes fixed to opposite sides and with the outlet 3 inches higher than the inlet.

EXPERIMENTAL DATA

The data obtained on the dust-collection efficiency of fibrous packing are presented in Table IV. Runs 1 and 2 must be discarded since the low collection efficiency of the Canton flannel resulted in the incomplete collection of the dust leaving the packed column, and consequently the collection efficiency for the packing is too high. It can be seen that there is considerable variation in the collection efficiencies among some runs at the same air rate on the 0.0125-inch-diameter wire packing. This is due to the fact that the flooding point is very sensitive to air rate for this type of packing. It is difficult to adjust the air rate so that enough oil is held up in the packing to wash the wires and yet not so much that oil is carried over to the filter.

PREDICTION OF EFFICIENCY FOR THE EXPERIMENTAL CONDITIONS

Collection efficiencies were predicted for the experimental runs described in Table IV and also for two of Calkins' runs. The predictions were carried out in different ways in order to gain some insight into the following questions:

1. Does mixing of the air stream in the cross-current direction within the packing occur to a significant degree?
2. Is it necessary to be conservative and use the experimentally determined collection efficiencies of Ranz and Wong, or are the higher efficiencies predicted by Langmuir and Blodgett sufficiently accurate?

TABLE IV

DATA FOR DUST-COLLECTION EFFICIENCY RUNS

Run No.	Packing	Oil Rate, lb/min	Air Rate, cfm	Air Velocity, ft/sec	Collection Efficiency Weight %	Remarks
1	12 layers of	.08	23.2	6.7	98.5	Canton flannel used
2	0.0125" wires on		23.2	6.7	95.0	for filter in runs
3	1/8" centers		23.2	6.7	82.2	1,2; SAE No. 10 oil
4			23.2	6.7	93.6	used in runs 1,2,3;
5			23.2	6.7	79.7	MSA No. 1106B paper
6			23.2	6.7	71.0	used for filter from
7			34.5	10.	93.5	run 3 on; SAE No. 30
8			34.5	10.	82.2	oil used from run 4
9			34.5	10.	92.9	on.
10			36.0	10.4	94.6	
11			36.0	10.4	92.4	
12			34.5	10.	95.5	
13			36.7	10.6	95.0	
14			36.7	10.6	94.0	
15	Knitted mesh		28.7	6.3	97.8	1.5" bed depth in
16	0.006"-dia. wire		28.7	6.3	97.5	runs 15 - 18;
17			21.8	4.8	87.3	packing not flooded
18			21.8	4.8	90.8	in runs 17, 18;
19			21.8	4.8	96.9	0.75" bed depth in
20			21.8	4.8	96.6	runs 19, 20.

The significance of these questions will become apparent from the discussion which follows.

The bases for the predictions of dust collection efficiencies are the relationships shown graphically in Fig. 1. These show the collection-efficiency relationships for single collector elements of various shapes. In order to apply these to the problem of predicting the efficiency of a bed or group of elements, the bed must be defined in terms of the effect of the group on behavior of an individual within the group. As an example of a group of collector wires, the array shown in Fig. 4 is considered. The array is composed of 10 wires whose diameters are 1/10 the width of the flow channel and which are arranged so that they sweep the entire area of the flowing stream. This is comparable to the usual filter bed with a porosity of over 99% although the length of the flow element in Fig. 4 should be drawn twice as long as it is if it were drawn to scale.

With an inlet air stream of known dust loading there is little question about the situation at the first wire. It encounters the stream and collects a fraction of the dust of each size as indicated by the product of its collection efficiency for the size times the fraction of the air stream it encounters. In this case the fraction collected would be 0.17 since one tenth of the cross-sectional area of flow is intercepted by the wire.

Now the question is: "What is the dust concentration in the air stream impinging on the next wire?" Is it the same as that impinging on the first wire, or has there been sufficient mixing in the air stream behind the first wire so that the concentration is reduced by the amount caught by the first wire? We can set up equations to describe both of the extreme cases. If there were no mixing in the cross-current direction, the total collection efficiency for the array in Fig. 4 would be the same as that for a single collector since the entire cross section of the stream is swept once.

$$\eta_{Dt} = \eta_D \tag{1}$$

where η_{Dt} is the total collection efficiency for particles of diameter = D, and η_D is the collection efficiency of one wire for particles of diameter = D.

If there were complete mixing so that the dust concentration is uniform across the air stream approaching any wire, the fraction of the original concentration which is present in the plane following the first wire would be

$$C_D = (1 - 0.1\ \eta_D) \tag{2}$$

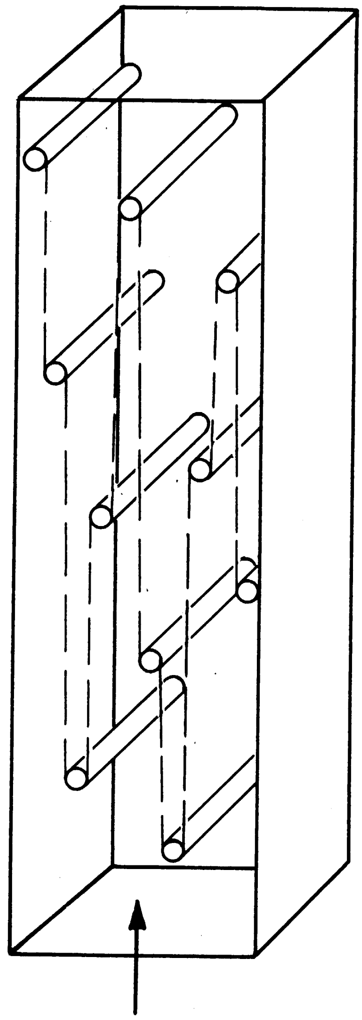


Fig. 4. Array of collector wires.

where C_D is the concentration of particles of diameter = D, expressed as a fraction of the initial concentration.

The fractional concentration C_D can also be called the fractional penetration. For example, if η_D were 1.0, the fraction of the dust collected by this array would be 0.1 and the fraction penetrating the first layer of wire would be 0.9. Further, the second layer would pass 0.9 of the dust passing it, so the penetration after the second stage would be 0.9 x 0.9 = 0.81. It can be seen from the above that the total collection efficiency of n layers of wires for the case of complete mixing is given by Equation 3, below:

$$\eta_{Dt} = (1 - C_{Dt}) = 1-(1 - 0.1\ \eta_D)^n \quad . \qquad (3)$$

Now, the results given by Equations 1 and 3 are compared for the array in Fig. 4. Consider the case where η_D is 1.0 for all particles larger than diameter D. If it is assumed that no mixing occurs, Equation 1 indicates 100% collection of all particles larger than diameter D. If it is assumed that complete mixing occurs, Equation 3 becomes:

$$\eta_{Dt} = 1-(1 - 0.1)^{10} = 1 - .35 = .65 \quad .$$

Thus, there would be 65% collection of all particles larger than diameter D.

Collection efficiencies for the experimental runs were computed on the basis of both extreme cases of mixing effect. The comparison of the efficiencies predicted for both assumptions with the experimental data will then indicate whether one or the other assumption is adequately accurate or whether some intermediate condition must exist. The computation of collection efficiency involves the following steps:

1. Determine the collector wire spacing within the bed and the fraction of the flow cross section blocked by the wire in any layer. It is assumed that the fibers are located at regular intervals and that the average spacing may be computed from the porosity (volume percent voids) of the bed. The porosity is related to fiber spacing and diameter by Equations 4 and 5 below.

For a square grid,

$$(1-X) = \frac{\frac{\pi d^2}{4}}{a^2} \qquad (4)$$

for a hexagonal grid,

$$(1-X) = \frac{\frac{\pi d^2}{4}}{\frac{3a^2}{2\sqrt{3}}} \quad . \tag{5}$$

where X = porosity (volume % voids); d = wire diameter (cm); and a = distance between wires (cm).

The fraction of the flow cross section blocked by wire in any layer is given in Equation 6:

$$Y = \frac{d}{a} \tag{6}$$

where Y = fraction of flow cross section blocked by wire in any layer.

For these computations, it was assumed that the grid is square (except for packing A) and thus the distance between wires in a layer is the same as the distance between layers. The dimensions of the packing materials investigated are given in Table V.

2. Determine the single-element collection efficiency versus particle size relationships for known value of wire diameter, air velocity, air viscosity, and particle density. This is based on the relationship shown in Fig. 1 for collection efficiency versus inertial parameter.

3. Determine the relationship between collection efficiency for a single wire and efficiency for the entire bed. The most convenient way to carry this out is in terms of penetration or $(1 - \eta_{tD})$. If the calculation is based on the assumption of no mixing, then the relationship can be given by the general form of Equation 1.

$$C_{Dt} = (1 - \eta_D)^{nY} \quad . \tag{7}$$

The exponent in Equation 7 has been called the number of stages of collection. In other words, the product nY is equal to the number of times the entire cross section of the air stream is swept in its passage through the bed.

If the calculation is based on the assumption of complete mixing, then the relationship for total efficiency is given by Equation 3.

4. Determine the fraction of the test dust penetrating the packing. This is conveniently done by multiplying the fractional penetration for any diameter by the size distribution function, $F_{(D)}$, for that diameter.

The distribution function is the slope of a percent undersize versus diameter curve and consequently has the units of weight percent per

TABLE V

DIMENSIONS OF PACKING MATERIALS

Material	Bed Density, gm/cc	Porosity, %	Wire Dia, in.	"a" Distance between wires, in.	"Y"	"n" Number of Layers of Wire
(A) 12 layers of 0.0125" dia wire			0.0125	0.125	0.075	12.
(B) 1.5" deep bed of 0.006" dia wire mesh	0.127	0.9833	0.006	0.041	0.146	36.6
(C) (Calkins' data) 1.26" deep bed of steel wool	0.0775	0.99	0.0031	0.03	0.105	42.4

micron. Thus, the total area under the curve in a plot of $F_{(D)}$ versus D is equal to 100%. If the computed values of penetration ($C_D \times F_{(D)}$) are plotted versus D, the area under the curve is equal to the total percent penetration for that particular size distribution.

Sample calculations based on both assumptions of degree of mixing are given in Table VI. Plots of the distribution function versus diameter showing the size distribution of the initial and penetrating dust for several systems are given in Figs. 5, 6, 7, and 8. Comparisons of the experimental and predicted collection efficiency are given in Table VII.

DISCUSSION OF RESULTS

The most striking feature of the comparison of predictions with experimental results is that the assumption of no mixing is reasonably accurate. Runs 3 to 9, on the 0.0125-inch wire grids, show this most effectively. In this case there is so little wire in the bed that even if each wire were 100% efficient for all sizes, the total efficiency could be no more than 71.8% if there were complete mixing. Yet the data show efficiencies in the regions of 80% and 90% for the air velocities used. It is obvious that the assumption of no mixing gives an answer much closer to the experimental one.

It can also be seen that for many types of air-cleaning equipment the distinction is not too important since the difference between the two methods decreases as bed depth increases. For shallow beds, such as some of the individual packing elements in engine air cleaners, the assumption of no mixing is necessary.

The results for the knitted wire mesh, runs 17 to 20, are not consistent and require some scrutiny. It is believed that runs 17 and 18 show the efficiency for the packing area used in the calculations while runs 19 and 20 show the efficiency for a smaller area since considerably more oil was held up in these runs. Consequently, the efficiencies obtained in runs 19 and 20 are for a higher linear velocity than is calculated from the air flowrate and the cross-sectional area of the packed section. If this is a valid interpretation, then the experimental efficiency is about 8% lower than the predicted efficiency. The explanation for this lies in the fact that the wires in the knitted mesh do not lie in horizontal planes, but rather are looped so that parts of the wire are parallel or inclined to the flow, and at some points two wires are drawn together. Consequently, the wires are not as efficient as they would be if the strands were all oriented in a plane perpendicular to the flow.

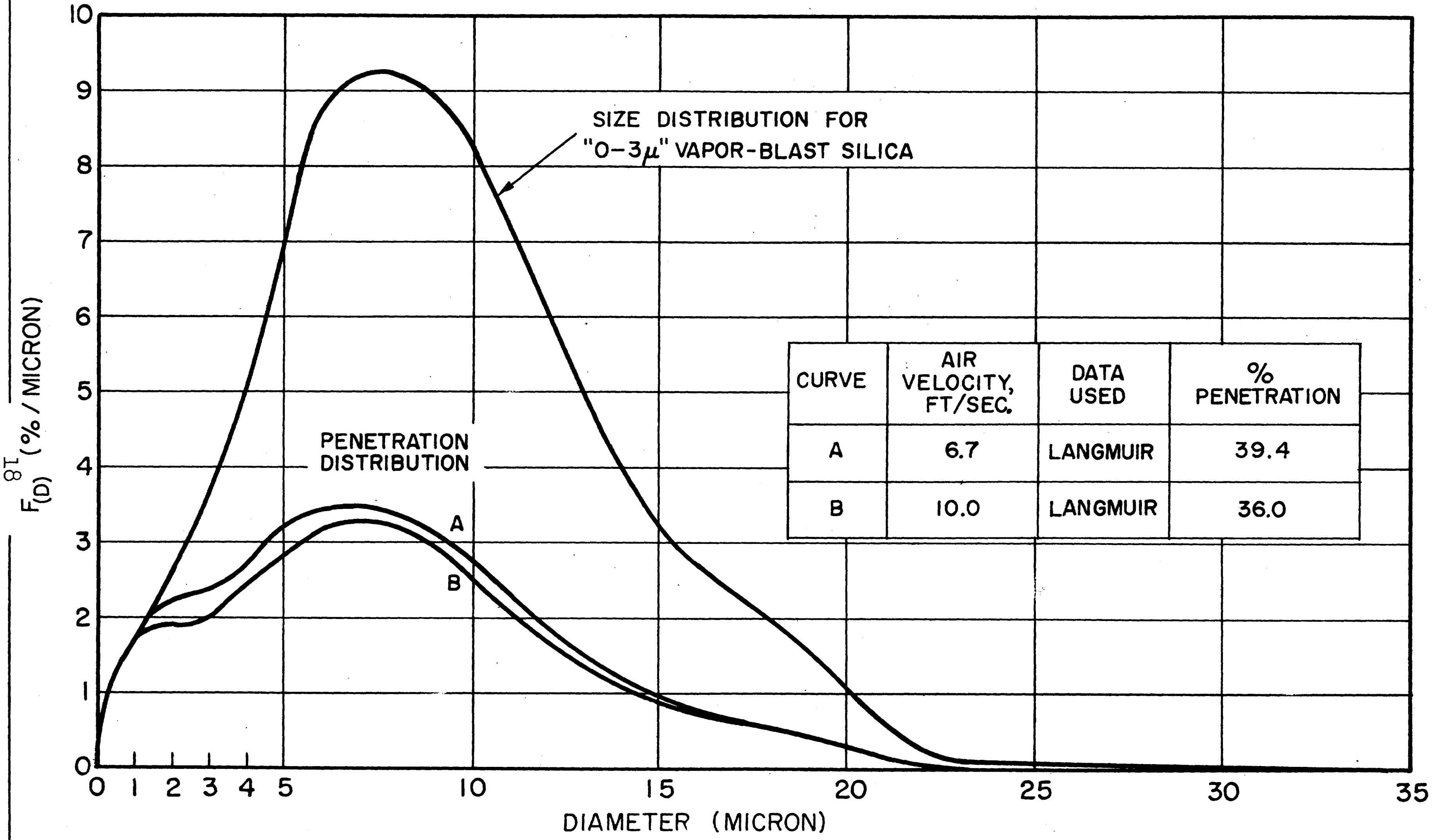


Fig. 5. Predicted collection efficiency for 0.0125-inch-diameter wire grids, assuming complete mixing.

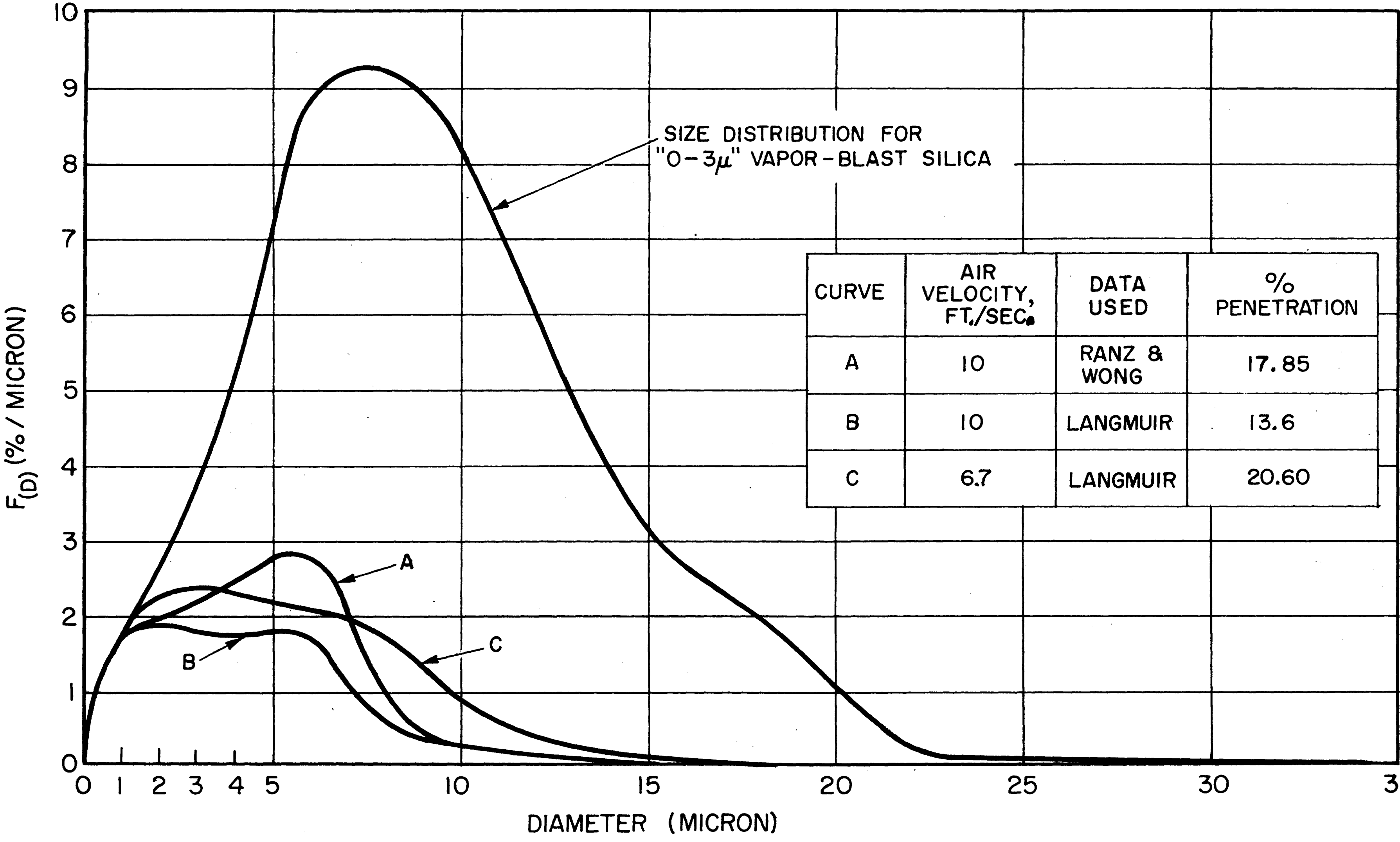


Fig. 6. Predicted collection efficiency for 0.0125-inch-diameter wire, 12 grids, assuming no mixing.

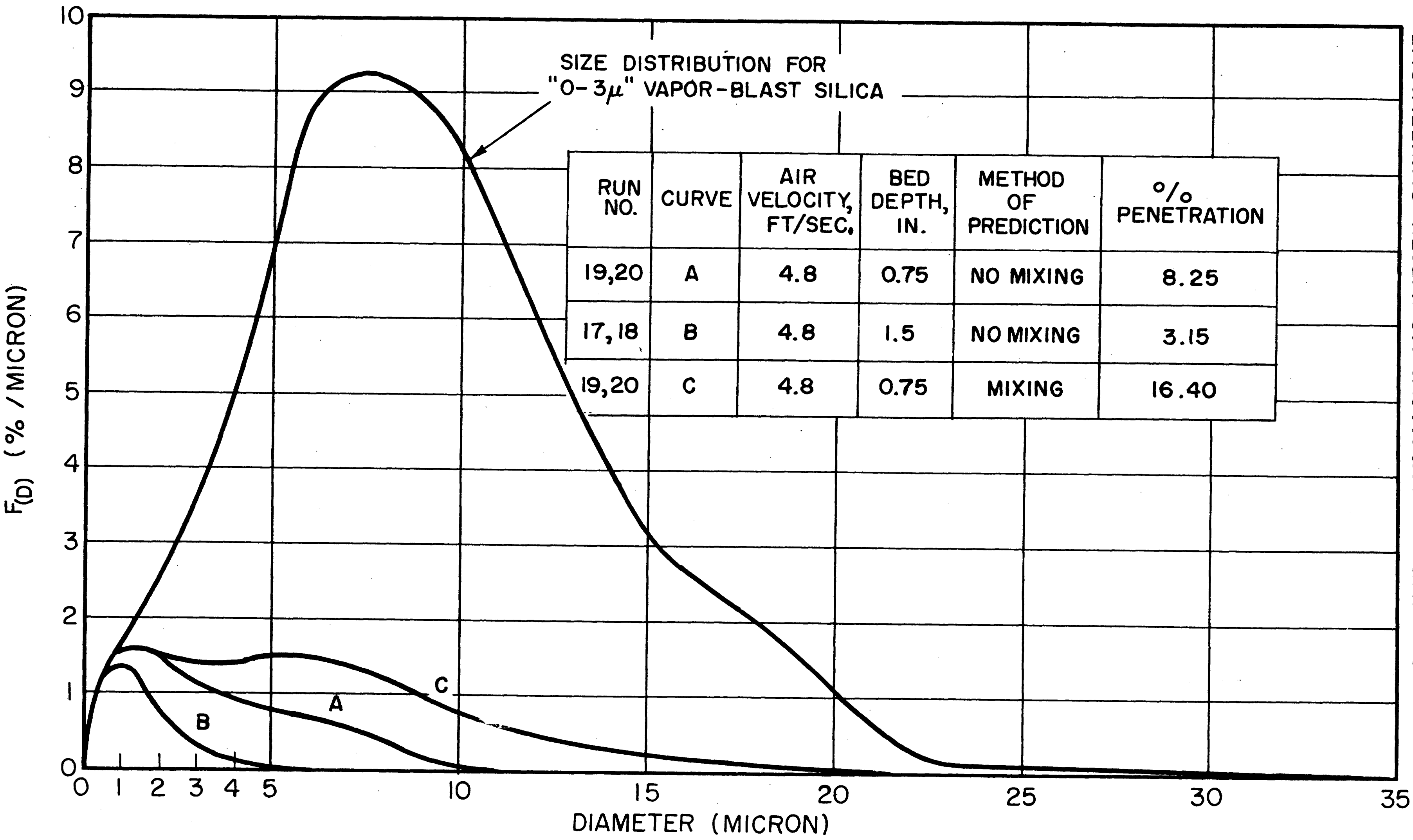
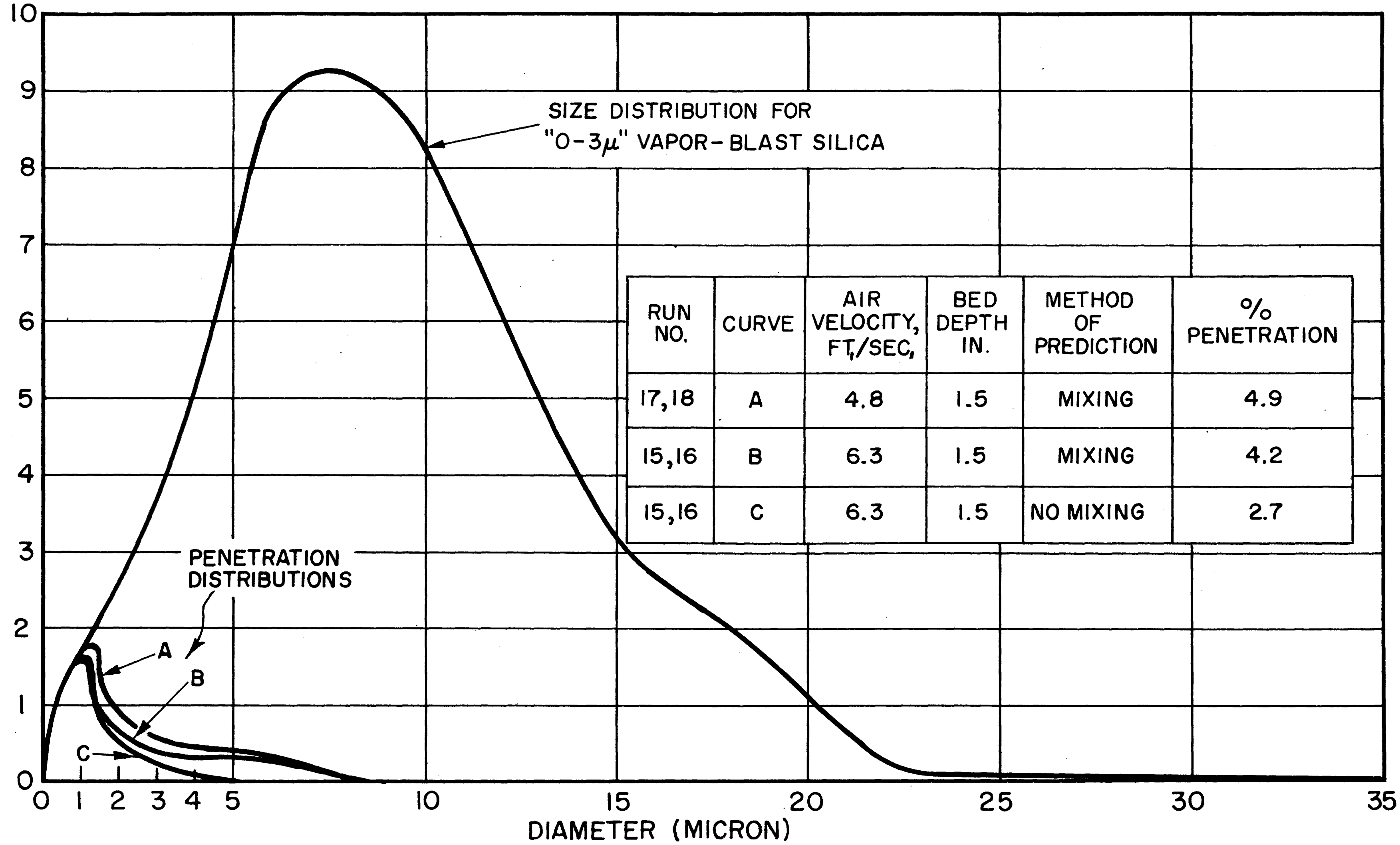


Fig. 7. Predicted dust penetration for 0.006-inch-diameter wire mesh.



RUN NO.	CURVE	AIR VELOCITY, FT./SEC.	BED DEPTH IN.	METHOD OF PREDICTION	% PENETRATION
17,18	A	4.8	1.5	MIXING	4.9
15,16	B	6.3	1.5	MIXING	4.2
15,16	C	6.3	1.5	NO MIXING	2.7

Fig. 8. Predicted dust penetration for 0.006-inch-diameter wire mesh.

TABLE VI

SAMPLE CALCULATION OF COLLECTION EFFICIENCY FOR A 0.75-INCH DEEP BED OF WIRE MESH
(Packing Type B)

Basis: No mixing, nY = 2.6 (stages), air velocity = 4.8 ft/sec

D (microns)	η_D (Fraction)	$(1-\eta_D)2.6$	$F(D)$	$F(D) \times C_D$
1.5	.1	.76	2.1	1.60
2.0	.2	.56	2.6	1.46
3.3	.4	.265	4.0	1.06
5.5	.6	.092	8.1	0.74
9.1	.8	.015	8.8	0.13
12.0	.9	.0025	6.0	0

Basis: Complete mixing, n = 18.3 (layers), air velocity = 4.8 ft/sec

D (microns)	η_D	$(1-\eta_D)18.3$	$F(D)$	$F(D) \times C_D$
1.5	.1	.761	2.1	1.60
2.0	.2	.58	2.6	1.51
3.3	.4	.34	4.0	1.36
5.5	.6	.19	8.1	1.54
9.1	.8	.105	8.8	0.93
16.0	1.0	.057	2.7	0.154

TABLE VII

COMPARISON OF PREDICTED AND EXPERIMENTAL COLLECTION EFFICIENCIES

Run No.	Experimental Collection Efficiency, %	Predicted Collection Efficiency: Assuming No Mixing	Predicted Collection Efficiency: Assuming Complete Mixing	Remarks
Calkins No.6	96.0	97.7	87.2	Packing C, 0.625" bed
Calkins No.9	97.6	98.8	97.22	Packing C, 1.25" bed
Our Runs:				
No. 3,4,5,6	81.6*	79.4	60.6	Packing A
No. 7,8,9	89.5*	86.4	64.0	Packing A
No. 15,16	97.7*	97.3	95.8	Packing B, 1.5" bed
No. 17,18	89.0*	96.85	95.1	Packing B, 1.5" bed
No. 19,20	96.8*	91.75	83.6	Packing B, 0.75" bed

*Average efficiency for all runs indicated.

It should be noted that while the data are sufficient to establish a basis for computation of efficiency with reasonable accuracy, they do not define the situation completely. The main area of doubt concerns the particle size of the dispersed test dust. It is almost certain that the dust size as dispersed is larger than the size analysis indicates. With the type of dust feeder employed in obtaining the data cited here (an ejector type was used by Calkins as well as by us), the amount of agglomeration is small, but it does exist. Consequently, the experimentally determined efficiencies are slightly higher than they would be for the size dust indicated by the sedimentation analysis.

The other point which should be made is that the assumption of no mixing is not strictly correct, even though it is a good approximation. It is obvious that some mixing will occur because of the turbulence in the air stream in the wakes of the wires. However, the presently available data are not extensive enough to permit any closer evaluation of the mixing effect than has been made. It would be worthwhile to extend the data on the wire grids (packing A) to cover the effect of variations in wire spacing.

A comparison of the efficiency data of Ranz and Wong with that of Langmuir and Blodgett is shown in curves A and B on Fig. 6. It can be seen that there is a significant difference for the collection of the larger particles by a shallow bed. For deeper beds this difference in the total efficiency is lessened because of the overshadowing effect of a large number of collection layers or stages. While it is more conservative to use the Ranz and Wong data for design, the Langmuir data yield a closer check with experiment for the data at hand.

CONCLUSIONS

As the result of the analysis of the experimental data on collection efficiency, the following conclusions can be drawn:

1. The dust-collection efficiency of fibrous packing can be predicted to within an average of 2%.

2. The assumption of no mixing of the air stream within the packing bed should be used in preference to the assumption of complete mixing.

3. The collection-efficiency data of Langmuir and Blodgett (see Fig. 1) should be used as the basis for efficiency predictions.

4. Further experimental work is required to fix more exactly the effect of mixing on collection efficiency.

5. The collection efficiency of randomly oriented fibers, such as knitted mesh, cannot be predicted with as much accuracy as for oriented fibers. The deviation must be determined experimentally and was as high as 7%.

PRESSURE DROP FOR AIR FLOW THROUGH FIBROUS PACKING

The relationship between pressure drop and the flow of air through fibrous packing has been studied by previous investigators and has been expressed in terms of rather cumbersome empirical correlations. In an effort both to simplify and generalize the mathematical description, equations have been derived here to describe the behavior of a bed of fibers in terms of an individual fiber and its drag coefficient. This resulted in an equation which is adequately accurate except for the cases of high packing density and for irregular fibers, such as steel wool.

The case of flow through beds of steel wool has been treated with an empirical correlation which must be regarded as an approximation. This is due to the fact that there is great variation in the sizes, shapes, and roughness of the fibers within a given commercial size grade. The effect of packing density is taken into account in the correlation for steel wool, but has not been studied to any extent for cylindrical fibers. That there is an effect of packing density has been shown by both the data on fiber beds and that on drag coefficients for groups of objects.[5] The data on fiber beds show that for spacings greater than about 8 diameters there is no appreciable effect on one fiber's behavior by the surrounding fibers. Thus, even without accounting for the effect of fiber spacing, the derived relationship is of immediate value in application to low-density packings, which are used to a large extent in oil-bath air cleaners. The effect of fiber spacing will be studied further in future work.

PRESSURE DROP FOR BEDS OF CYLINDRICAL FIBERS

The form-drag force acting on the individual fibers is assumed to be the significant frictional effect in the system consisting of a fluid flowing through a bed of fibers oriented with their major axes perpendicular to the direction of flow. Air is the fluid and steel wool is the fiber of immediate interest, so the final equation contains a constant evaluated in terms of the properties of these. It is also assumed that all the fiber are oriented in the same plane and that bed density or fiber spacing has no effect upon drag coefficient.

The drag force acting on the fibers is given as:

$$F = C_D A_W \frac{\rho_G v^2}{2 gc} \quad . \tag{8}$$

The pressure drop is related to the drag force by a force balance as:

$$\Delta P = \frac{F}{Ac} \quad ; \tag{9}$$

Thus:

$$\Delta P = C_D \frac{A_W \rho_G v^2}{A_c 2 gc} \quad . \tag{10}$$

And since,

$$\rho_B = \frac{\pi r_W^2 l \rho_W}{A c L} \tag{11}$$

and

$$A_W = 2 r_W l \tag{12}$$

Substitution of Equations 11 and 12 into 10 will result in Equation 13 below:

$$\Delta\rho = \frac{C_D v^2 \rho_B \rho_G L}{\pi \rho_W r_W gc} \quad . \tag{13}$$

For convenience in using Equation 13 for air flow through a bed of steel wool, substitutions are made to incorporate the following factors:

ρ_G = 0.075 lb/cu ft,
ρ_W = 7.8 (62.4) lb/cu ft,
ρ'_B is in gm/cc,

$\Delta\rho''$ is in inches of water, and
$r''w$ is in inches.

Then:

$$\frac{\Delta P''}{L} = 2.2 \times 10^{-4} C_D \frac{\rho_{B'} v^2}{r''W} \quad . \tag{14}$$

Nomenclature:

A_c = conduit area, sq ft

A_W = wire projected area, sq ft

C_D = drag coefficient (dimensionless)

F = drag force, lb

gc = gravitational constant, 32.17 (ft/sec^2)

G = gas rate, cu ft/sec

L = bed length, ft

l = fiber (or wire) length, ft

ΔP = pressure drop across bed, lb/cu ft

$\Delta P''$ = pressure drop across bed, inches H_2O

r_W = wire radius, ft

r_W'' = wire radius, in.

v = gas velocity based on void area = $\dfrac{G}{A_C\left(\dfrac{1-P_B}{P_W}\right)}$ (ft/sec)

V = gas velocity based on conduit area = $\dfrac{G}{A_C}$ (ft/sec)

ρ_B = bed density, lb/cu ft

ρ_B' = bed density, gm/cc

ρ_G = gas density, lb/cu ft

ρ_W = wire (or fiber) density, lb/cu ft

If the values of drag coefficient are taken from Fig. 9,[3] and substituted in Equation 14, one can compute values of $\frac{P''}{L\ B'}$ for various air velocities. The results of such computations are shown in Fig. 10, a plot of predicted pressure drop versus air rate for beds of cylindrical steel wire. A similar plot may be made for any other wire material by correcting for the wire density.

The general relationship (Equation 13) was used to predict the pressure drop for the flow of air through beds of glass fiber.[7] A comparison of predicted with experimental values is given in Table VIII below.

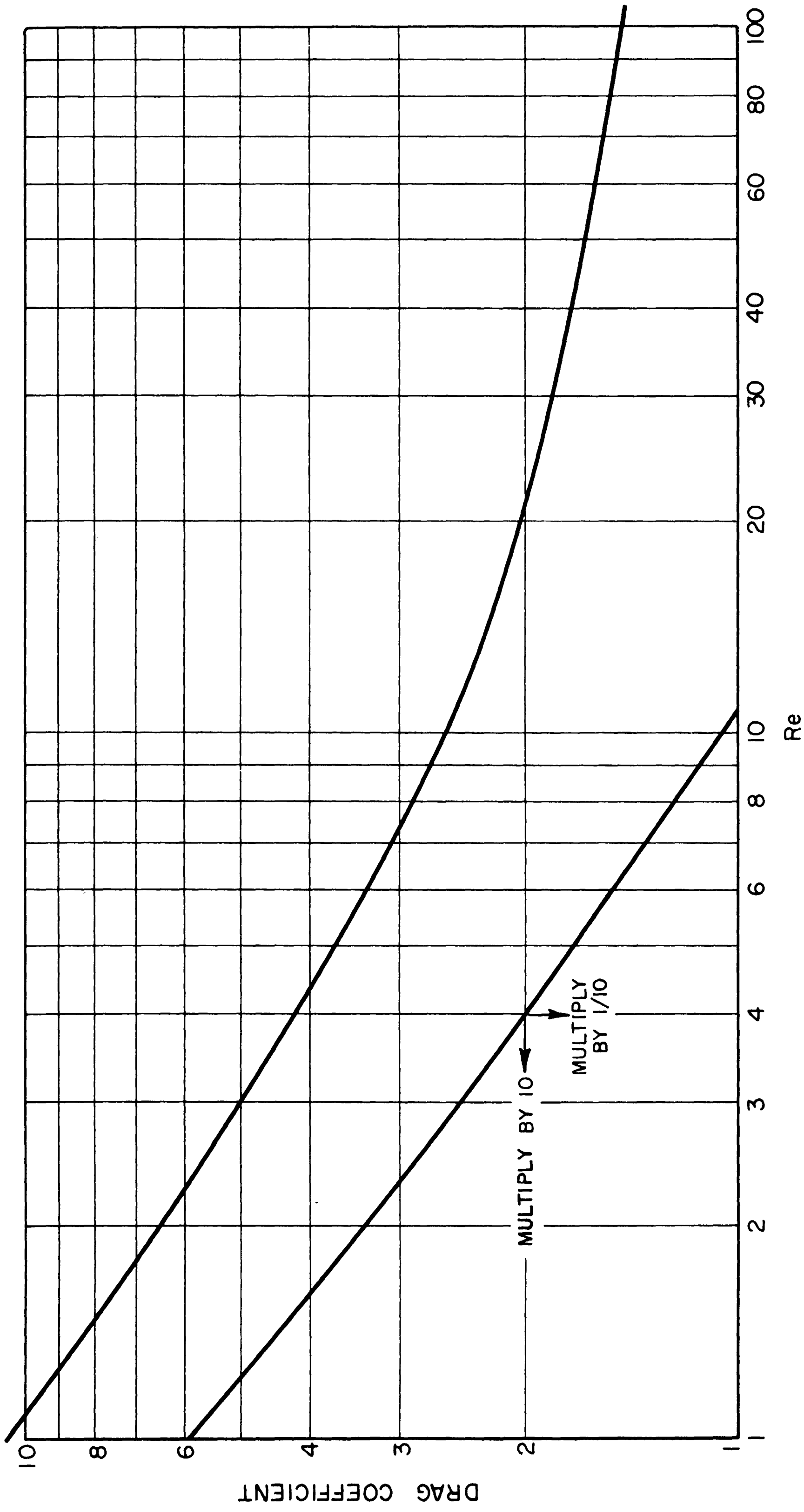


Fig. 9. Drag coefficient vs Reynold's number (Reference 3, p. 1018).

TABLE VIII

COMPARISON OF PREDICTED AND EXPERIMENTAL PRESSURE DROPS
FOR THE FLOW OF AIR
THROUGH BEDS OF FIBERGLAS PACKING[7]
(Air velocity is 20 ft/min for all cases.)

Type of Fiber	115 K	115 K	115 K	AA
Fiber diameter	0.00115"	0.00115"	0.00115"	1.28μ
Bed density, lb/cu ft	1.5	3.0	6.0	1.2
Bed depth, in.	12	10	20	1.0
Experimental pressure drop, in. water/ft bed	0.1	0.288	0.804	2.2
Predicted pressure drop, in. water/ft bed	0.1	0.222	0.444	2.0
Distance between fibers (R_D), in fiber diameters	9.2	6.5	4.6	10.3

These data indicate that the method of prediction is satisfactory for low-density beds, but that there is a definite effect of bed density which is not taken into account. The limited amount of data available at present has not permitted an evaluation of this effect although it is planned that future work under this contract will complete this aspect of the study.

When the data on pressure drop for beds of steel wool were compared to the predictions shown in Fig. 10, it was seen that the method of prediction was inapplicable. Considerable effort was expended on attempts to correlate the behavior of steel-wool beds with the drag coefficient analysis, but it was not possible to do so. The difficulty seems to be due to the wide variation in fiber shape and size within a grade of steel wool. Although it might be possible to account for these variations by a detailed study of the fibers, it did not seem advisable since steel wool is not an important packing material for engine air-cleaner use. Consequently, the description of the steel-wool data by an empirical correlation was considered adequate for the purpose of this study.

EXPERIMENTAL WORK

The pressure-drop data for several grades of steel wool were taken from a 2-3/4-inch-diameter packed column. The steel wool was supported by

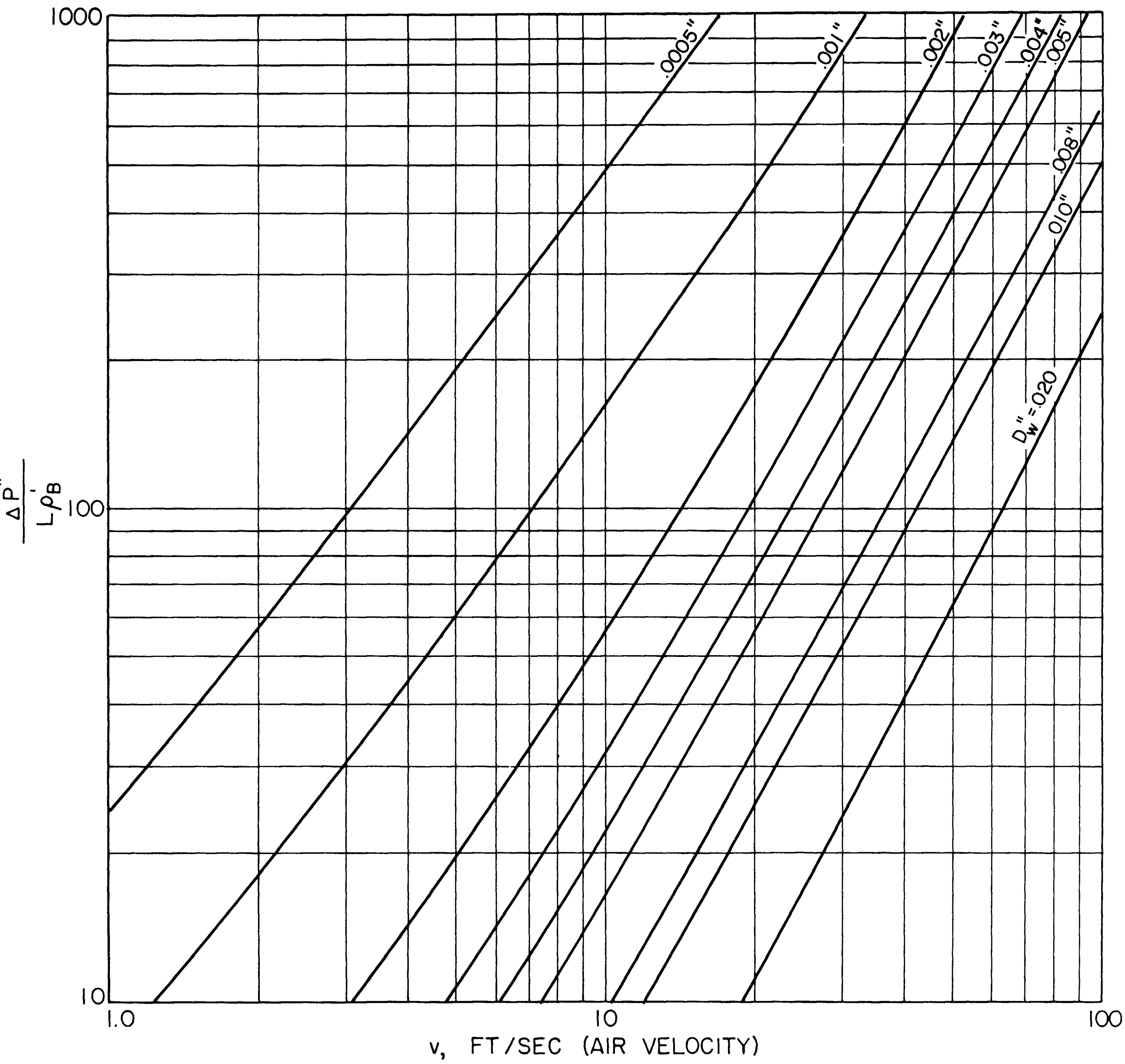


Fig. 10. Predicted pressure drop group vs air velocity for air flow through beds of round steel wire.

Based on:

$$\frac{\Delta P''}{L\rho'_B} = 2.2 \times 10^{-4}\, C_D \frac{v^2}{r''_w} = \frac{''\, H_2O}{ft \times gm/cc}$$

$(\rho_{air} = .075$ lb/cu ft, $\mu_{air} = .018$ CP).

"bulls-eye" rings and compressed to any desired depth by a bulls-eye on top of the packing. Thus the bed density could be computed from the weight of steel wool used and the bed depth and diameter. The average fiber diameter was determined for each grade of wool on the basis of average fiber volume as computed from the weight of 25 fibers, 6 inches long.

The data obtained for "Supreme" brand steel wool can be represented by the following equation:

$$\frac{\Delta P}{L\ \rho_B'} = 0.021 \left(\frac{v^{1.7}}{R_D^{0.5}\ D_W^{1.1}} \right) \qquad (15)$$

where

v = superficial linear velocity, ft/sec
R_D = ratio of wire spacing to wire diameter
D_W = wire diameter, in.

The wire spacing is calculated on the basis that the wires are arranged in a square grid. In this case the spacing is given by the following equation:

$$d = r_W \sqrt{\frac{\pi \rho_W}{\rho_B}} \ . \qquad (16)$$

While Equation 15 fits the data for "Supreme" brand steel wool to within $\pm$ 5%, it predicts pressure drops which are about 35% too high for "Elephant" brand. Obviously, the differences in fiber shape and size distribution are not taken into account by the mean diameter based on volume. The correlation will be given an order of magnitude prediction, however, which is adequate for the preliminary evaluation of a packing. If and when more accurate data are required for a particular type of steel wool, it would probably be as easy to get the actual pressure-drop data as to make a detailed study of the size distribution and shape for use for a more refined correlation. In view of this, along with the relative unimportance of steel-wool packing, the subject was left at this point.

FLOODING POINTS IN FIBROUS PACKING

The flooding point of a packed column is the gas rate at which liquid is blown upward and out of the packing. It is dependent (1) on the rate at which liquid is fed into the packing although it does not vary much at low liquid rates, (2) on the ability of the liquid to flow out of the packing in the face of a given gas velocity rather than on the ability of the gas to flow drops of liquid off the packing fibers, and (3) on the viscosity of the liquid but not to any significant extent on its surface tension.

The data on fibrous packing which were taken in this investigation can be correlated satisfactorily by the Sherwood[6] method of correlation which was based on data for Raschig rings and similar column packing. Two fibrous packings, No. 3 steel wool and grids of 0.0125-inch-diameter copper wire, and three oils, SAE No. 10, 20, and 30, were used in a 3-1/3-inch-ID column. The equipment has been described earlier in this report under collection efficiency. It consisted, essentially, of a means for passing air upward through the packing and spraying oil on top of the packing.

Flooding was determined by visual observation of the packed bed. Because the bed must accumulate liquid in order to flood, it is necessary to approach the flooding point very slowly. In spite of such precaution, there is still an area of uncertainty as can be seen in the scatter of the data shown in Figs. 11 and 12.

A correlation of flooding points for Raschig rings and other common types of tower packing was presented by Sherwood and is shown in Fig. 13. The symbols are defined in a note on the figure. Points from the smooth curves drawn through our data are plotted in terms of this correlation along with Sherwood's lines on Fig. 14. Values of the parameters used are given in Table IX. The data would be well represented by an extension of Sherwood's lines for large columns (this extension is indicated by the dashed line).

TABLE IX

VALUES OF PARAMETERS FOR EXPERIMENTAL PACKINGS

Description of Packing	S (ft^2/ft^3)	F (ft^3/ft^3)	D_W" (Wire Dia, in.)
2" deep bed of No. 3 "Elephant" brand steel wool, horizontal fiber orientation, bed density = 0.035 gm/cc.	41.	0.986	0.00528
2" deep bed of same steel wool as above, bed density = 0.07 gm/cc.	82.	0.981	0.00528
0.9" deep bed of grids of 0.0125"-dia copper wire on 1/8" centers, layers 0.075" apart.	50.	0.977	0.0125

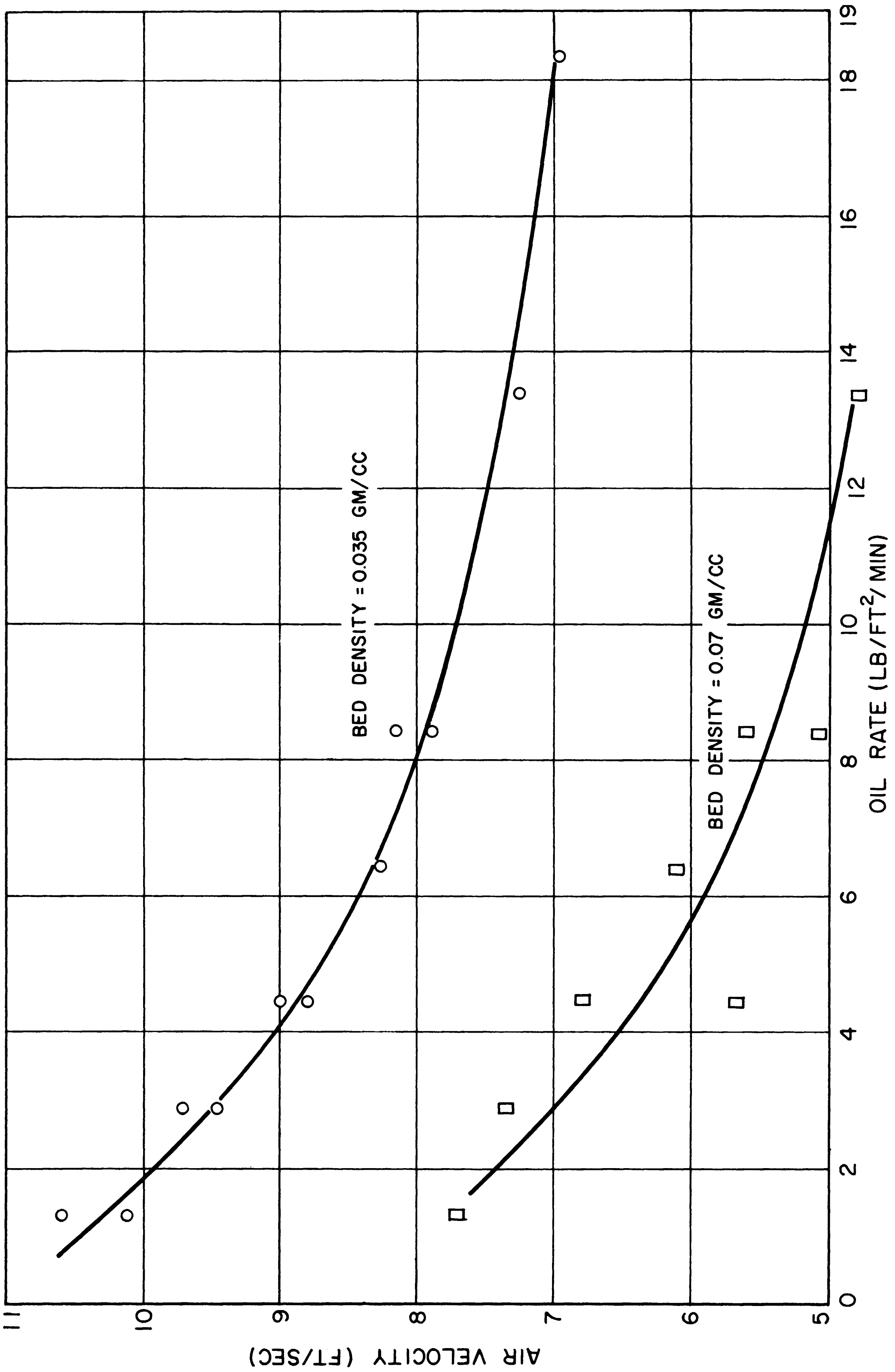


Fig. 11. Flooding points for 0.00528-inch-diameter, No. 3 steel wool (air and SAE No. 10 oil).

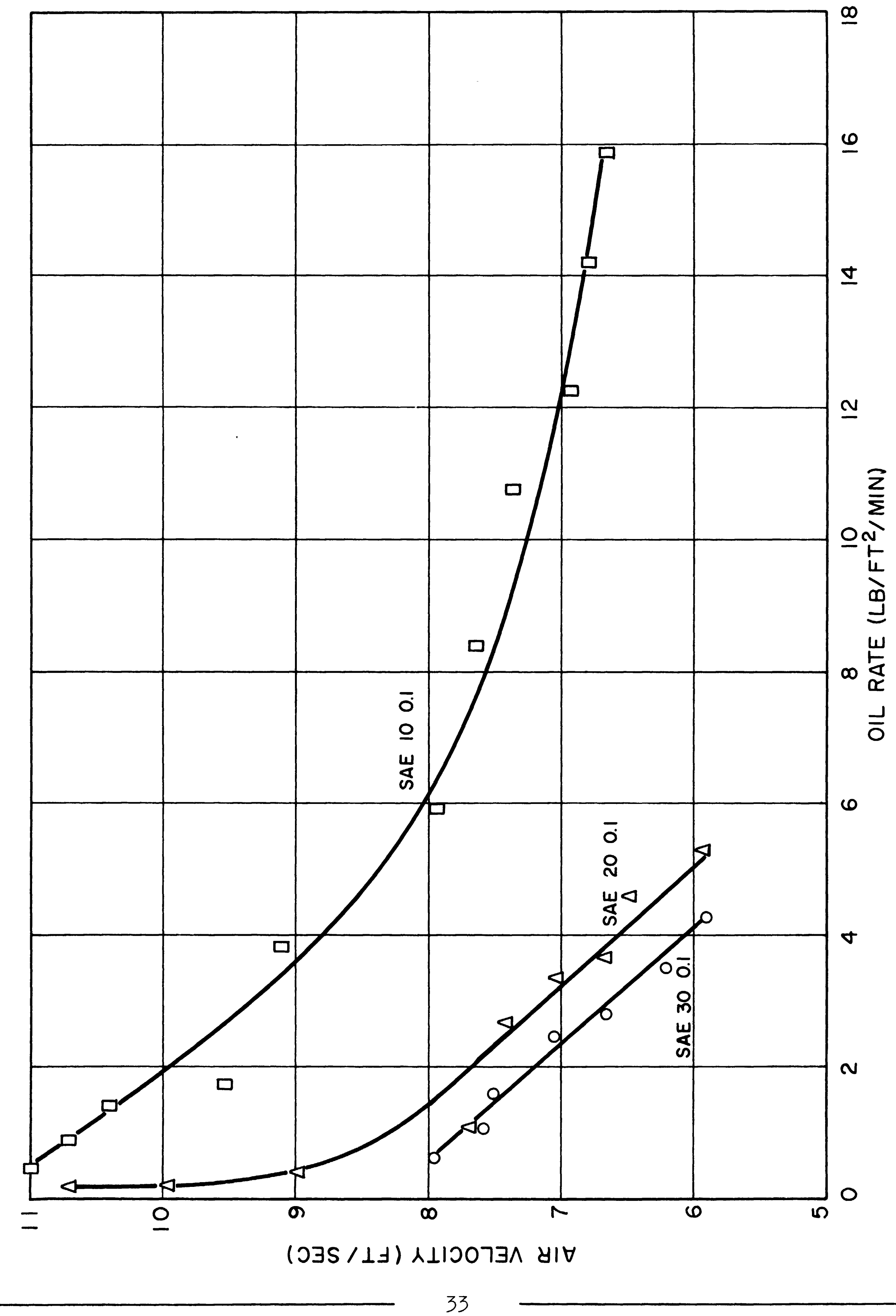


Fig. 12. Flooding points for 0.0125-inch-diameter wire grid (air and lube oil).

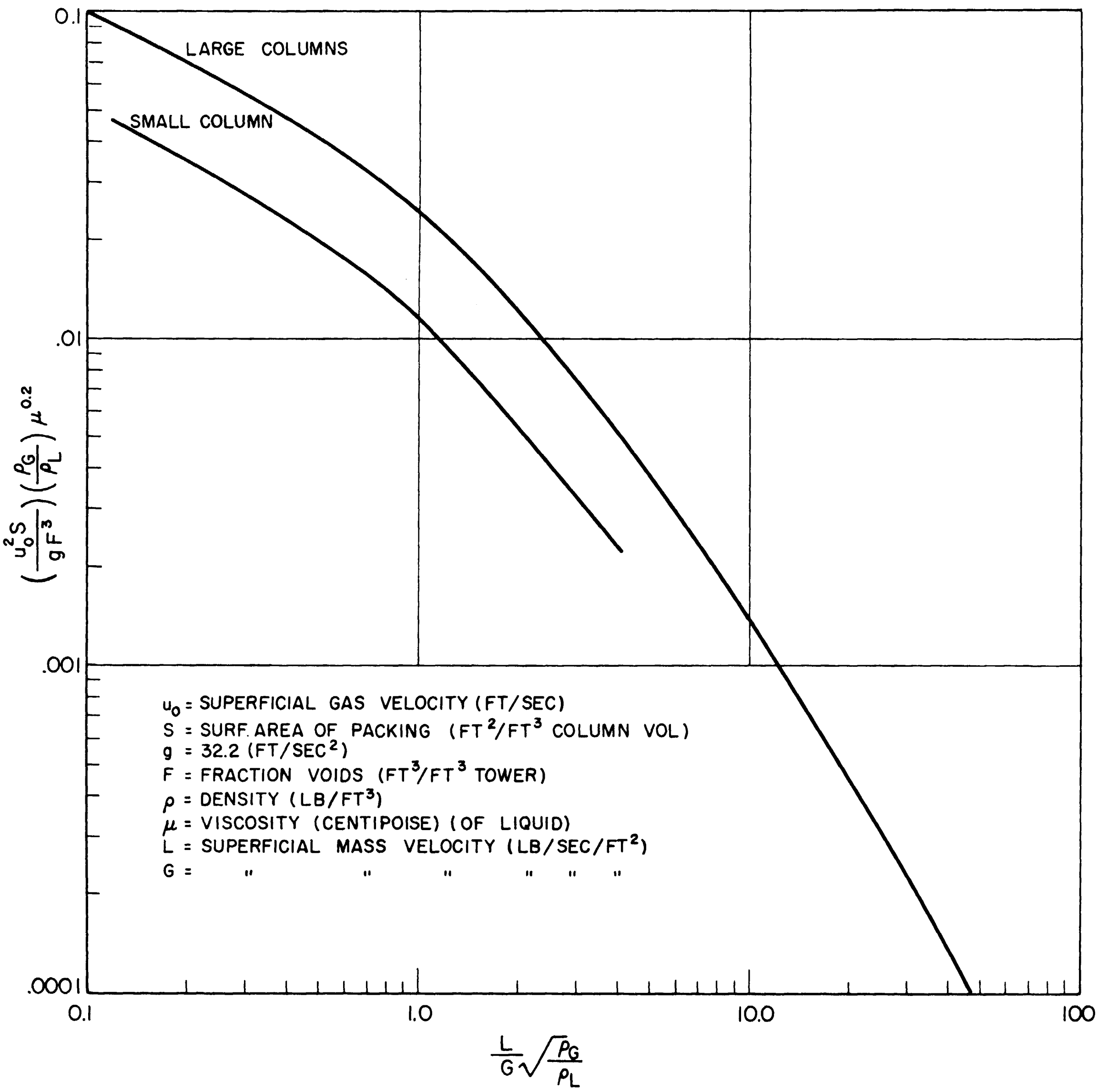


Fig. 13. Flooding-point correlation.[6]

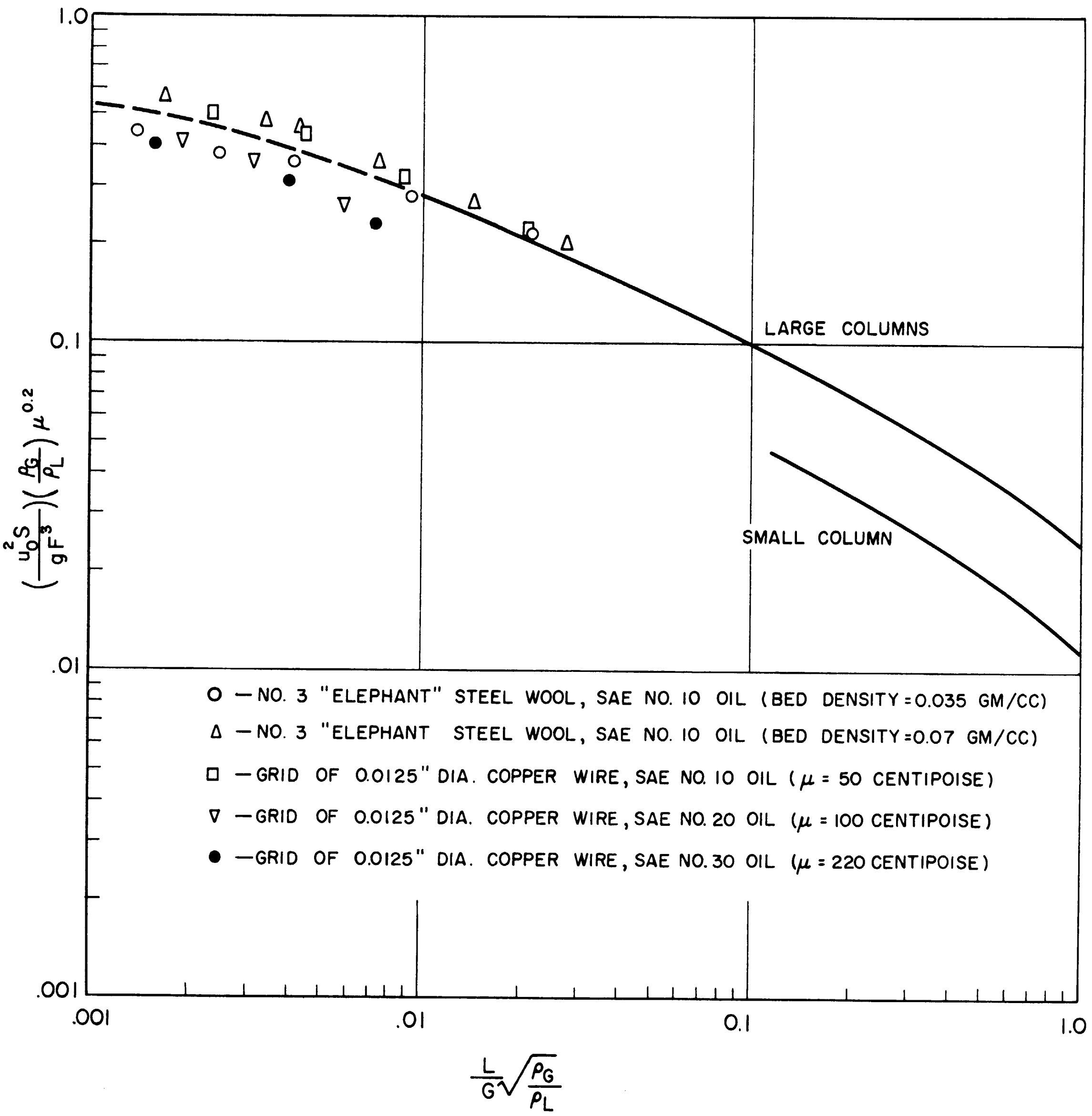


Fig. 14. Flooding-point correlation for fibrous packing.

MECHANISM OF FLOODING

The mechanism by which flooding occurs seems to be related to the ability of the liquid to drain out of the packing, rather than to the ability of the air to blow drops off the packing. This is indicated by the data of Sherwood which shows that the flooding point depends on the density and viscosity of the liquid, but not on its surface tension. If flooding were defined as the condition under which drops would be blown off the packing, then surface tension would be important since it is the major force holding the liquid to the packing.

In view of the mechanism of flooding, it is apparent that the method of introduction of liquid is not significant. The ability of a packing to hold up a given amount of liquid at any given air velocity will be the same whether the liquid is run in at the top or sprayed into the bottom of the packing. Thus the data for packed columns with counter-current flow should be valid for systems such as the packed section of an engine air cleaner.

The direct application of the flooding point correlation to the problem of flooding in oil-bath air cleamers can not be made without knowing the relationship between liquid holdup and the flowrates. Liquid holdup in an air cleaner is determined by the amount of oil which can be blown out of the baffle cup. Flooding points for an air cleaner should thus be stated in terms of the air rate which causes flooding for a given quantity of holdup per volume of packing. The determination of this relationship remains for future work.

REFERENCES

1. Calkins, R. G., "Filter Scrubber Dust Collectors," Presented at the American Chemical Society Annual Meeting in New York, September, 1954.

2. Calvert, S., "The Prediction of Dust Removal in an Oil-Bath Air Cleaner," Interim Technical Report, University of Michigan, Engineering Research Institute Project 2233, July, 1954.

3. Perry, John H., Chemical Engineers Handbook, McGraw-Hill Book Company, New York, 1950.

4. Ranz, W. E. and Wong, J. B., "Impaction of Dust and Smoke Particles," Ind. Eng. Chem., 44, 1371 (1952).

5. Rouse, H. and Siao, T., "Form Drag of Composite Surfaces," Presented at the Second U. S. National Congress of Applied Mechanics, 1954.

6. Sherwood, Shepley, and Holloway, "Flooding Velocities in Packed Columns," Ind. Eng. Chem., 30, 765 (1938).

7. Freidlander, S. K., et al., "Handbook on Air Cleaning," U.S. Atomic Energy Commission, Washington, D. C., 1952.