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Engineering Experiment Station
University of Illinois

September 15, 1954

Technical Report No. 13

DEPOSITION OF SUSPENDED PARTICLES
FROM TURBULENT GAS STREAMS

by

S. K. Friedlander, Research Assistant

Contract No. AT(11-1)-276

U. S. Atomic Energy Commission

H. F. Johnstone, Technical Director

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DEPOSITION OF SUSPENDED PARTICLES
FROM TURBULENT GAS STREAMS

by

S. K. Friedlander, Research Assistant

Engineering Experiment Station
University of Illinois
Urbana, Illinois

September 1, 1954

ABSTRACT

The deposition of suspended particles from turbulent streams was studied by passing suspensions of small particles in air through tubes of varying diameter at different velocities. Particle transfer coefficients were calculated from the deposition rates and concentrations. The rates of deposition were determined by counting under a microscope the particles deposited in a given time on a known area of tube wall. The concentration of the aerosol was measured by passing a known volume through a Millipore filter and counting the particles deposited on the filter. Turbulent deposition was found to be an inertial effect; the rate increased rapidly as the particle diameter and gas velocity increased. The data were correlated by means of an analysis of the von Karman type, assuming that the particles diffused to within one stopping distance of the wall.

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I. INTRODUCTION

The purpose of this work was to investigate experimentally and theoretically the deposition of suspended particles from turbulent gas streams. The rate of deposition depends on two factors: the rate of transport of the particles from the turbulent gas to the wall, and the behavior of the particles at the wall, i.e., adhesion to the wall or to other particles, rebounding, or reentrainment. The second effect was investigated only incidentally to the first. Precautions were taken to ensure the adhesion of all particles that struck the wall, and only a single layer of particles was allowed to accumulate on the surface.

The aerosols used in the research were composed of iron and aluminum particles, and Lycopodium spores with densities of 7.80, 2.70, and 1.175 g./cc., respectively. The mean particle diameters were 0.8, 1.57, 1.81, 2.63, and approximately 30 microns. The turbulent field was established by passing the aerosols through 0.54, 1.3, and 2.5 cm. tubes, at Reynolds numbers ranging from 2,100 to 35,000. The deposition was measured in the region of fully developed turbulence by counting the individual particles under a microscope. In most cases, the concentration of the aerosol was measured by passing

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a known volume of gas through a Millipore filter and counting the particles on the surface of the filter. The results are reported in terms of a "particle transfer coefficient", defined as

$$k = N_o/c_{av} \quad (1)$$

where k is in cm./min.

II. THEORETICAL BACKGROUND

A considerable amount of experimental and theoretical work has been done on mass transfer from turbulent gases. One of the most successful theoretical approaches is that of von Karman (13) who expresses the shear stress as

$$\tau = (\mu + \rho \epsilon_g) \frac{dv}{dy} \quad (2)$$

and gives the velocity distribution across the duct in a generalized manner as

$$\text{laminar sublayer} \quad (0 < y^+ < 5) \quad v^+ = y^+ \quad (3)$$

$$\text{buffer region} \quad (5 < y^+ < 30) \quad v^+ = 5 + 5 \ln \frac{y^+}{5} \quad (4)$$

$$\text{turbulent core} \quad (y^+ > 30) \quad v^+ = 5.5 + 2.5 \ln y^+ \quad (5)$$

If it is assumed that the eddy diffusivities of mass and momentum are equal, the rate of mass transfer can be written

$$N = (D_{BM} + \epsilon_g) \frac{dv}{dy} \quad (6)$$

The eddy diffusivity in the laminar sublayer is assumed to be zero and that for the buffer region can be obtained from Equations 2 and 4. Equation 6 can be integrated for the laminar and buffer regions. In the turbulent core, the Reynolds analogy is assumed to hold. In this manner, the following expression is obtained for the mass transfer coefficient

$$\frac{k}{v_{av}} = \frac{f/2}{1 + \sqrt{f/2} \left\{ 5(N_{Sc} - 1) + 5 \ln \left[\frac{5N_{Sc} + 1}{6} \right] \right\}} \quad (7)$$

This analysis is satisfactory when the molecular diffusivity of mass, D_{BM} , is approximately equal to the kinematic viscosity of the fluid, that is, $\mu/\rho D_{BM} \sim 1$. For very large or very small values of the Schmidt number, however, von Karman's approach must be modified. Lin, Moulton, and Putnam (7) studied the transfer of dissolved substances of very low diffusivity (high Schmidt number) and found, in order to explain their own data and those of other investigators, that it was necessary to assume the presence of fluctuations in the "laminar" sublayer. On an empirical basis, they found that the data could be correlated if the eddy diffusivity in the sublayer is

$$\epsilon_g = \sqrt{\left(\frac{y^+}{24.5}\right)^3} \quad (8)$$

The effect of small fluctuations in the sublayer on the transfer of momentum and on the velocity distribution is slight since, even at the edge of the sublayer where it is a maximum, $\epsilon_g = \frac{\sqrt{}}{24.5}$.

Although the eddy diffusion of gases from turbulent streams has been studied with some success, the behavior of suspended particles in a turbulent field is not well understood. Only a few experiments have been reported (1, 8, 9), and the theory is undeveloped.

Alexander and Coldren (1) studied the deposition of water droplets on the walls of a 1.86 inch pipe through which air was passed at Reynolds numbers ranging from 80,000 to 300,000. The water spray was introduced by means of an atomizing nozzle located axially at the duct inlet. In the analysis of their data, they concluded that the pipe could be divided

into an inlet region in which the disturbing effects of the atomizing nozzle were important and a second region of fully developed turbulent flow for which transfer coefficients were measured. No experimental data on drop diameters were taken, but a mean drop size of 27 microns was calculated from an empirical expression for air atomizing nozzles.

Longwell and Weiss (8) studied the mixing and distribution of liquids in high velocity air streams. They concluded that the eddy diffusivity of a particle is less than that of a gas because of the inertia of the particle. Towle and Sherwood (12) found that the eddy diffusivities of hydrogen and carbon dioxide were essentially the same even though the molecular weight of carbon dioxide is 22 times that of hydrogen. Based on these data, Sherwood (10) suggested that the eddy diffusivity of molecules, or of very fine dust particles may be independent of their mass.

Rumpf (9) studied the formation of deposits on the walls of ducts through which material in gaseous suspension was passed. He was concerned principally with the conditions at the wall, which determine the stability of the deposit, and less with the process of transport from the turbulent gas. He discussed the effect of the type of particles and surface, the particle size distribution, and the velocity gradient in the neighborhood of the wall on the adhesive forces between particles and wall. Tests were made on the rate of turbulent deposition using a limestone dust classified into two fractions, above and below 12 microns. With the coarse fraction, no deposit was observed at velocities between 60 and 165 ft./sec., but when the finer fraction was used, deposition of the particles

occurred rapidly. Rumpf concluded that, in the accumulation of a wall deposit, a layer of small particles forms first and the larger particles then adhere to this base.

III. EXPERIMENTAL

A. Apparatus

Three types of powders were used: two grades of iron powder, obtained from the Antara Chemicals Division of the General Dyestuff Corporation, with mass median diameters of approximately 3 and 5 microns, respectively, and a standard geometric deviation of about 1.4 (4); an aluminum powder of approximately 5 microns mean diameter, from the Reynolds Metals Company; and Lycopodium spores, obtained from McKesson and Robbins, of about 30 microns diameter (3). The powders were dispersed by a glass atomizing nozzle with a throat 16 mm. long and 3 mm. i.d. The compressed air for the nozzle was passed first through a glass fiber filter and then through a pressure regulating valve. Before passing through the observation tube, the aerosol flowed through a 5 gallon drum fitted with a mixing baffle at the inlet. The aerosol stream from the nozzle played directly on the baffle where it was joined by sufficient room air to make up the desired flow rate. The aerosol was drawn through the system by a rotary positive blower.

The observation tubes were made either of glass or of brass. Their arrangement in the system is shown in Figure 1. The dimensions of the tubes are given in Table 1. The smaller glass tubes were made of thin wall Pyrex glass. The observation regions on these tubes were made by grinding down the wall and polishing the flat surface with No. 150 Carborundum powder using a flat brass strip and an oil lubricant. The observation sections for the brass tubes were made by cutting windows three inches long and replacing the cut-out sections with new pieces machined to fit the opening.

Table 1. Dimensions of Observation Tubes

Material	Diameter cm.	Distance from Inlet to Obser- vation Region cm.	Total Length cm.	L_t/D
Glass	0.54	24	33	44.5
Glass	0.58	entrance region tube		
Glass	1.305	42	60	32.2
Glass	2.50	89	118	35.5
Brass	1.38	48 and 74	91.5	34.8 and 53.7
Brass	2.50	65	109	26

A glycerine-jelly adhesive and "pressure sensitive" Scotch tape were used in some runs to prevent reentrainment of the particles from the walls of the duct. The composition of the glycerine jelly was that given by Gregory (3): 1 gram gelatin, 7 grams glycerine, 6 cc. water, and 1% phenol. In the runs with the 1.3 cm. glass tube, the jelly compounded according to this formula was diluted with 20 cc. of water to make it less viscous.

Millipore filters, from the Lovell Chemical Company, were used to determine the concentrations of the iron and aluminum aerosols. These filters were Type HA for hydrosol assay and were 47 mm. in diameter. Isokinetic flow through the sampling tube was obtained by using a tapered brass probe with the proper tip diameter. As shown in Figure 1, the probe was inserted, through a tee section, into the top of the observation tube so that the gas did not flow around any bends on the way to the filter.

A rotary pressure and vacuum pump was used for sampling the aerosol.

Before each run, the section of duct on which the deposition was observed was carefully cleaned. For the 0.54 and 1.3 cm. glass tubes, this was accomplished by boiling in a solution of detergent in de-mineralized water. The amount of deposition in the brass tubes and the 2.5 cm. glass tube was determined in one of three ways: (1) In some cases, the wall was cleaned of particles initially by applying a piece of regular Scotch tape and stripping it off; at the end of the run, the deposit was removed for counting in the same way by another piece of tape. (2) In other runs, a piece of pressure sensitive tape was affixed to the test section before starting, and removed at the end of the run. (3) In the Lycopodium runs, molten glycerine jelly was applied to the removable section and then allowed to drain.

The formation of the deposit in the 0.54 and 1.3 cm. glass tubes was observed while the run was in progress. In general, the runs lasted between 5 and 30 minutes. When the particles deposited too rapidly or when the deposition rate was inconveniently slow, the run was repeated with a different concentration of aerosol. The concentration was controlled by adjusting the amount of powder fed to the atomizing nozzle or, in some cases, by using only a fraction of the powder injected by the nozzle.

At the end of a run, the iron or aluminum particles on the wall and filter were counted under a microscope with a 95 x objective and a 15 x eyepiece. A calibrated Porton "globe-and-circle" graticule was used for measuring the particle size. In the runs with Lycopodium powder, the concentration of the spores was determined by passing a sample of gas through a glass fiber filter which was weighed before and after the run.

IV. RESULTS

In Figures 2 to 4, inclusive, the particle transfer coefficient is plotted against the Reynolds number for each type of particle. The theoretical curves, discussed later, are shown as dotted lines. In Figure 5, k is plotted against distance from the tube inlet with the Reynolds number as the parameter. The transfer rate, average concentration, transfer coefficient, average gas velocity, Reynolds number, reduced stopping distance, and values of k calculated from the theory are given in Tables 2 through 10.

The deposition rate was determined by counting at least 100 particles on a known area of the tube wall at the end of a run. A photomicrograph of a deposit of iron particles sensitive tape is shown in Figure 6.

At the start of the work, before the extreme sensitivity of the transfer rate to particle size was recognized, particles were counted from a range of sizes and a simple arithmetic average was taken. During the later runs, efforts were made to limit the particle size counted to as narrow a range as possible. Table 11 shows the particle sizes used in the calculations and the ranges which these represented.

The iron particles were easy to size since they were nearly all spherical and only a small percentage were present as agglomerates. The aluminum powder was more difficult to size, since it consisted mostly of spherical and pear-shaped particles with a small percentage of flakes. The runs with the Lycopodium spores at high velocities were not reproducible and only the low velocity runs are reported. All of these runs were made in the 2.5 cm. brass tube with the glycerine jelly adhesive on the wall. A high velocity (55 ft./sec.) run was made with pressure sensitive tape but no particles adhered to the surface.

Table 2. Deposition of 0.8 Micron Fe Particles in 0.54 cm.
Glass Tube

Run	No particles/ (cm. ²) (min.)	c _{av} particles/ cc.	k cm./min.	V _{av} ft./sec.	N _{Re}	S ⁺	k _{calc} cm./min.
0	13,850	8,300	1.669	66.8	7,450	1.5	11.95
3	46,900	7,680	6.1	87.1	9,700	2.38	
4	58,500	8,920	6.64	87.1	9,700	2.38	
5	0	--	0	18.8	2,100		
6	4,330	18,850	2.29	66.8	7,440	1.482	
7	33,200	1,436	23.1	106	11,900	3.44	
9	33,300	662	50.3	106	11,900	3.44	
11	37,800	631	59.8	106	11,900	3.44	
12	36,900	1,061	34.9	106	11,900	3.44	
13	0	29,900	0	26.9	3,000		
14	5,060	29,900	0.1692	43	4,790	.67	1.5
15	66,500	1,510	44.1	107.1	11,950	3.45	
16	39,500	14,900	2.65	62.5	6,950	1.316	
17	61,900	895	69	131	14,580	4.96	547
19	15,750	166	95	131	14,580	4.96	
20	19,400	42.2	460	180	19,400	8.33	
21	24,500	55.0	445	180	19,400	8.33	

Table 3. Deposition of 0.8 Micron Fe Particles in 1.3 cm.
Glass Tube

Run	N_0 particles/ (cm. ²)(min.)	c_{av} particles/ cc.	k cm./min.	V_{av} ft./sec.	N_{Re}	S^+	k_{calc} cm./min.
22	0	725	0	28.4	7,660		
23	700	5,800	0.1205	40.9	11,020	.52	
24	4,640	6,960	0.667	47.1	12,720	.671	
25	4,810	6,600	0.73	53.7	14,500	.85	
26	3,710	8,960	0.413	47.1	12,720	.671	
27	5,590	3,290	1.7	60.4	16,300	1.051	
30	17,900	4,250	4.21	78.1	21,100	1.67	
31	46,600	2,750	16.95	104.3	28,200	2.81	66.2
32	103,000	1,155	68.0	131.0	35,400	4.23	265
57	2,460	6,630	0.371	34.5	9,330	.385	.376
58	3,270	7,100	0.462	46.5	12,550	.655	
59	9,630	7,380	1.305	58.9	15,900	1.01	4.26

Table 4. Deposition of 1.81 Micron Aluminum Particles in 1.38 cm. Brass Tube Using Pressure Sensitive Tape

Run	N _o particles/ (cm. ²)(min.)	c _{av} particles/ cc.	k cm./min.	V _{av} ft./sec.	N _{Re}	S ⁺	k _{calc} cm./min.
116	850	4.89	174	95.2	27,200	4.17	188
117	1,226	3.8	323	108.9	31,100	5.31	
118	1,925	146	13.2	68.7	19,630	2.32	27.7
119	416	163	2.55	42.6	12,170	.975	2.92
120	3,030	36.4	83.3	85.4	24,400	3.43	
121	585	44.3	13.2	53.1	15,180	1.455	
126	321	186.5	1.725	46.7	13,350	1.16	
127	951	96	9.91	60.4	17,250	1.83	
128	1,203	28.1	42.8	76.3	21,800	2.8	49.1

Table 5. Deposition of 1.57 Micron Fe Particles in 1.3 cm.
Glass Tube

Run	N _o particles/ (cm. ²)(min.)	C _{av} particles/ cc.	k cm./min.	V _{av} ft./sec.	N _{Re}	S ⁺	k _{calc} cm./min.
52	5,030	5,370	0.936	19.5	5,270	.499	0.381
53	9,830	6,110	1.486	26.5	7,150	.863	
55	93.4	5,640	0.01656	11.62	3,140	.196	0.0361
56	14,900	4,570	3.26	34.4	9,300	1.39	
60	14,340	2,000	7.17	40.6	10,950	1.85	
61	19,100	1,942	9.83	44.1	11,900	2.15	
62	5,480	3,010	1.82	31.3	8,450	1.17	3.26
63	10,850	1,095	9.93	48.9	13,200	2.60	
65*	5,650	1,555	3.63	34.5	9,310	1.39	
66*	25,700	280	92	59.0	15,950	3.66	80.3
67*	25,000	345	72.4	59.0	15,950	3.66	
68*	6,600	461	14.3	43.4	11,700	2.1	
69*	12,290	520	23.6	52.6	14,200	2.96	40.6
70*	16,050	384	41.7	59.0	15,950	3.66	
124a**	56,200	158.5	348	85.3	24,400	7.45	
125a**	60,000	211	284	68.5	19,600	5.04	

*Wall coated with glycerine jelly adhesive

**1.38 cm. brass tube with pressure sensitive tape

Table 6. Deposition of 0.8 Micron Fe Particles in 2.5 cm. Tubes

Run	N _o particles/ (cm.) (min.)	c _{av} particles/ cc.	k cm./min.	V _{av} ft./sec.	Re	S ⁺	k _{calc} cm./min.
38*	2,740	3,710	.738	39.7	20,600	.432	0.503
40*	2,630	2,860	.92	45.4	23,600	.55	
41*	3,920	4,400	.89	50.6	26,300	.671	
42*	4,960	2,960	1.675	67.4	35,100	1.13	5.72
43*	3,330	14,530	.229	27.0	14,050	.217	
44*	2,210	5,600	.395	32.3	16,800	.428	
45***	5,280	15,800	.334	27.0	14,050	.217	0.0862
47**	1,585	5,290	.3	38.1	19,850	.403	
48**	7,330	4,950	1.48	50.6	26,300	.671	
49**	5,760	3,400	1.695	67.4	35,100	1.13	
113***	874	660	1.322	58.5	30,500	.86	

*Brass tube, bare wall.

**Glass tube, bare wall.

***Brass tube, pressure sensitive tape.

Table 7. Deposition of 1.32 Micron Fe Particles in 2.5 cm. Brass Tube
Using Pressure Sensitive Tape

Run	N _o particles/ (cm. ²) (min.)	C _{av} particles/ cc.	k cm./min.	V _{av} ft./sec.	N _{Re}	S ⁺	k _{calc} cm./min.
129a	5,030	231	21.8	58.9	30,500	2.40	24.9
130a	1,250	206	6.07	41.7	21,600	1.288	4.81
131a	797	263	3.03	27.8	14,450	.628	.78

Table 8. Deposition of 1.81 Micron Fe Particles in 2.5 cm. Brass Tube
Using Pressure Sensitive Tape

129	7,750	92.4	83.9	58.9	30,800	4.52	135.1
130	2,220	130.3	17.03	41.7	21,600	2.42	17.15
131	934	189.7	4.93	27.8	14,450	1.182	2.82
132	601	223	2.70	22.3	11,600	.795	.639

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Table 9. Deposition of 2.63 Micron Fe Particles in 2.5 cm. Brass Tube
Using Pressure Sensitive Tape

106	34,700	72.3	480	58.6	30,400	9.51	
107	13,650	219	62.3	27.8	14,410	2.48	14.1
108	2,230	69.5	32.1	27.8	14,410	2.48	
109	3,620	29.8	121.6	41.3	21,400	5.08	160
110	1,105	403	2.74	16.16	8,370	.931	
111	1,292	116.7	11.1	22.4	11,610	1.678	4.8
112	5,750	12.6	458	58.9	30,500	9.51	

Table 10. Deposition of Lycopodium Spores in 2.5 cm. Brass Tube
Coated with Glycerine Jelly Adhesive

Run	N_o particles/ (cm. ²) (min.)	c_{av} particles/ cc	k cm./min.	V_{av} ft./sec.	N_{Re}	s^+	k_{calc} cm./min.
83	217	1.66	131	20.6	10,690		
97	62.3	1.251	49.7	13.1	6,800	6.9	114
98	267	2.14	124.6	20.6	10,690		
99	384	5.77	66.5	14.87	7,700	8.64	157.6

Table 11. Ranges of Particle Sizes Counted

Nominal Size of Particle-microns	Type of Particle	Size Range microns
0.8	Fe	0.66 - 0.933
1.57	Fe	1.32 - 1.81
1.81	Fe	1.81 $\pm$ 0.2
1.81	Al	1.81 $\pm$ 0.2
2.63	Fe	2.63 $\pm$ 0.3

The concentration of the iron and aluminum particles was determined by counting at least 100 particles on a known area of the filter. A photomicrograph of a deposit of iron particles on the filter is shown in Figure 7. The concentrations, although measured at the axis, were assumed to be the average since the fraction of particles removed was small and, consequently, appreciable concentration gradients did not exist. The particle size ranges were the same as those used in counting the deposit.

The Lycopodium concentrations were determined by weighing the amount of dust filtered from a known volume of air and then multiplying the weight by the number of particles per gram, 9.39×10^7 , as determined by Gregory (3). This was permissible since preliminary tests with the Millipore filter showed that practically no agglomerates were present and all of the particles were essentially the same size.

V. DISCUSSION OF RESULTS

A. Behavior of Particles at the Wall

To ensure reproducibility and to simplify interpretation of the results it was important that all particles adhere to the wall after striking. Thus, it was necessary to avoid rebounding of the particles or immediate reentrainment by the gas stream. The course of deposition was followed under the microscope during several of the experiments, and when reentrainment began, either the adhesive was applied or pressure sensitive tape was used. As shown in Figures 3 and 4, the experiments with the adhesive agreed with those with the bare tube; in addition, experiments with glass and brass tubes checked each other. This indicated that rebounding was not important since there would be no reason to expect the same fraction of particles to rebound from the different types of surfaces employed.

Reentrainment of the 0.8 micron iron particles began in the 0.54 cm. tube at a Reynolds number of about 20,000; it began for the 1.57 micron iron particles in the 1.3 cm. tube at a Reynolds number of about 12,500. In general, it was observed that larger particles were more easily removed by the gas stream than smaller ones, so that, after running at a high velocity over a long period of time, the deposit might consist mostly of smaller particles even though the transfer rate increases with d_p^4 . This agrees with the results of Rumpf (9) who suggested that the larger particles are more easily torn from the wall.

B. Transport of Particles from Turbulent Gas

In the absence of thermal gradients, any of four mechanisms may be considered responsible for the transport of suspended particles to surfaces, viz., gravitational, diffusional, electrical, or inertial forces. It is worthwhile considering each of these in relation to the results of the present study.

1. Gravitational effects were eliminated by making most of the runs in vertical tubes. Some of these were checked against tests with horizontal tubes which had the observation point placed on the side; good agreement was always found.

2. A possible mechanism of transport is eddy diffusion in the turbulent core of the duct followed by Brownian diffusion through a stagnant region adjacent to the wall. Brownian diffusion is usually of importance only for particles smaller than about 0.2 microns. All of the particles used in this work were larger than 0.8 microns. The efficiency of removal by Brownian diffusion increases as the particle size decreases, since the diffusivity is inversely proportional to diameter. This fact is reflected in the analysis of von Karman (13) and of Lin, Moulton, and Putnam (7) by decreasing values of k/V_{av} , as N_{Sc} is increased at constant N_{Re} . But the data show that, at constant N_{Re} , k/V_{av} increases with about the fourth power of the particle diameter. Moreover, the deposition by Brownian diffusion decreases as the gas velocity increases since the particles have less time to reach the surface. This is reflected in the von Karman and Lin analyses by decreasing values of k/V_{av} as the Reynolds number is increased at constant N_{Sc} . The data, however, show that k/V_{av}

increases with about the third or fourth power of the velocity.

Thus, the evidence seems conclusive that Brownian diffusion through a stagnant region is not a controlling factor in the transport of particles larger than 0.8 microns from turbulent air.

3. At the start of the study some thought was given to the effect of electrical forces originating from charges acquired by the particles or from charges on the walls of ducts. That such effects might exist was illustrated during the first few runs with the 0.54 cm. glass tube. Before two of these runs, the inside walls were cleaned with lens paper; this caused a considerable increase in the deposition rate and the use of lens paper was abandoned in favor of boiling in a detergent solution. To check on the existence of electrical effects, three methods were used:

a. The deposition rate of the 0.8 micron iron particles was checked for a 2.5 cm. glass tube and for a 2.5 cm. brass tube. The results of these runs, which are shown in Figure 4, do not indicate any significant difference in the deposition rate between the two tubes. Since brass and glass have markedly different electrostatic properties, the tests indicate that electrical effects are of no importance.

b. The results of the experiments with the glycerine-jelly adhesive in the 1.3 cm. glass tube agreed well with the tests with the bare tube wall, as shown in Figure 3. In addition, a run with pressure sensitive tape in the 2.5 cm. brass tube agreed with similar runs with the bare tube wall. Thus, the nature of the surface seemed to have no significant effect on the deposition rate.

c. The results obtained with the aluminum particles, shown in Figure 3, were adequately correlated with the data on iron particles, on the basis of the inertial mechanism discussed later. For these two types of metallic particles, the electrical nature did not seem to have any significant effect on deposition.

In addition to these considerations, the efficiency of electrical precipitation usually decreases with increasing velocity (see, for example, Lapple, (5), p. 1040) since the particles have less time to migrate to the collecting surface. The data, however, show an increase of k/V_{av} with about the third or fourth power of velocity. Thus, it appears that electrical forces were not significant in this research.

4. There remains to consider the inertial effects. That these are of controlling importance is indicated by the rapid increase of the transfer rate with particle diameter and with gas velocity, which are typical inertial effects. The most likely mechanism of removal seems to consist of eddies moving towards the surface, changing their direction, and thereby casting out the particles which they carry. To test this hypothesis further, two runs were made in which 0.8 micron particles were passed through an 0.58 cm. glass tube, and the deposition rate was measured as a function of the distance from the tube entrance. With a smoothly rounded inlet section, the velocity at the entry to the duct is practically uniform over the cross section. At the wall, however, the fluid is retarded and a boundary layer forms and continues to grow. If the Reynolds number based on duct diameter is greater than 2,100, at some distance from the inlet the boundary layer becomes turbulent. This transition generally occurs at a

Reynolds number, based on distance from the entry, of between 10^5 and 10^6 , depending on the roughness of the wall and on the level of disturbance in the mainstream (2, p. 326). If the mechanism suggested for turbulent deposition is correct, the deposition rate in the entrance region should follow the development of the turbulent boundary layer. Figure 5, which shows the deposition rate as a function of distance from the inlet, confirms this hypothesis; no deposition occurred until N_{Re_x} reached about 10^5 , but the rate then increased, approaching a constant value at $N_{Re_x} = 2 \times 10^5$.

Figure 5 shows that the particle transfer coefficient reached a constant value in the region of fully developed turbulence. The same effect was noted with the 1.38 cm. brass tube when two tests were made on the deposition at observation points located 34.8 and 53.7 diameters from the inlet. With the exception of the entrance region tests, all measurements of transfer were made at points greater than 26 diameters from the inlet and thus all values of k are taken to be steady state values.

VI. THEORY OF TRANSPORT OF PARTICLES FROM TURBULENT GASES

Before discussing the transport of particles from turbulent gas streams the problem of diffusion of particles in homogeneous, isotropic turbulence should be examined. The particles with which we are concerned are much smaller than the scale of turbulence but sufficiently large that they do not exhibit Brownian motion. Two cases can be distinguished depending on whether the impaction parameter,

$\Psi = d_p^2 \rho_p v_p' / 18 \mu D_c$, based on the mean particle velocity and scale of turbulence is greater or less than one (9). The impaction parameter, so defined, is actually the ratio of the distance which a particle will move through an eddy, if the eddy suddenly comes to rest, to the size of the eddy. When this ratio is less than one, the particles will tend to remain with the same eddy and so diffuse with the gas. For a 1-inch pipe with $N_{Re} = 20,000$ and $\rho_p = 1$, $\Psi = 1$ if $d_p = 15$ microns, assuming that the mean particle velocity is equal to the mean fluctuating gas velocity and that the scale of turbulence is 1/7 of the pipe diameter (12, p. 37).

If Ψ is greater than 1, the particles will move from eddy to eddy. Assuming the applicability of Stokes' law, a force balance can be written for the "i"th particle, neglecting gravitational effects.

$$v_{gi} = v_{pi} + \frac{m}{K} \left(\frac{dv_p}{dt} \right)_i \quad (10)$$

Squaring both sides and taking mean values over all of the particles, we obtain

$$\overline{v_g^2} = \overline{v_p^2} + \frac{2m}{K} \overline{v_p \frac{dv_p}{dt}} + \left(\frac{m}{K}\right)^2 \overline{\left(\frac{dv_p}{dt}\right)^2} \quad (11)$$

Assuming that the mean energy of the particles is constant

$$2 \overline{v_p \frac{dv_p}{dt}} = \frac{d\overline{v_p^2}}{dt} = \frac{d\overline{v_p^2}}{dt} = 0 \quad (12)$$

and

$$\overline{v_g^2} = \overline{v_p^2} + \left(\frac{m}{K}\right)^2 \overline{\left(\frac{dv_p}{dt}\right)^2} \quad (13)$$

Equation 13 indicates that the mean square velocity of the particles is always less than that of the gas. According to the theory of diffusion by continuous movements (2, p. 217), the mean square displacement for a small volume of gas is given by

$$\overline{x_g^2} = 2 \overline{v_g^2} \int_0^T \int_0^t R_g d\theta dt \quad (14)$$

where $d\theta$ is an interval of time.

Similarly, the mean square displacement of a particle can be written as

$$\overline{x_p^2} = 2 \overline{v_p^2} \int_0^T \int_0^t R_p d\theta dt \quad (15)$$

The ratio of the eddy diffusivity of a particle to that of the gas is given by

$$\frac{\epsilon_p}{\epsilon_g} = \frac{\overline{x_p^2}}{\overline{x_g^2}} = \frac{\overline{v_p^2}}{\overline{v_g^2}} \frac{\int_0^T \int_0^t R_p d\theta dt}{\int_0^T \int_0^t R_g d\theta dt} \quad (16)$$

From Equation 13, $\overline{v_p^2}$ is less than $\overline{v_g^2}$ because of the inertia of the particles. But, for the same reason, the correlation coefficient between the velocities of a particle at two different times, R_p , is greater than the corresponding coefficient for the gas, R_g . Thus, the effects of inertia on ϵ_p tend to counteract each other.

In the discussion which follows, it is assumed that the eddy diffusivity of the particles is the same as that of the carrier gas. However, at the edge of a diffusing cloud of gas and particles, some of the particles tend to lag while others tend to move ahead of the gas because of their inertia. In the case of flow with a relatively stagnant boundary layer, particles are thrown from the turbulent core into the stagnant region. Consequently, the following model is hypothesized for the transport process in turbulent pipe flow: Eddies carrying particles diffuse from the turbulent core to within one stopping distance of the wall, and from this point the particles deposit as a result of their inertia. The stopping distance is the distance which a particle will move through a stagnant gas with a given initial velocity. It is given by the equation

$$S = \frac{m}{K} v_{po} \quad (17)$$

It is assumed that v_{po} is equal to the root mean square of the radial component of the fluctuating gas velocity $\sqrt{v_g'^2} = v_g'$. Actually, as pointed out above, the mean particle velocity is probably less than that of the mean gas velocity. Laufer (6) has measured experimentally the values of v_g' at Reynolds numbers of 50,000 and 500,000 in a 10 inch duct. In the region near the wall, the data for both Reynolds

numbers fall on the same curve when $v_g / \sqrt{f/2} V_{av}$ is plotted against y^+ , with $v_g / \sqrt{f/2} V_{av}$ increasing from zero at the wall to 0.9 at $y^+ = 80$, where the curve levels off. We shall assume that the mean particle velocity is $0.9 \sqrt{f/2} V_{av}$, that is, the particles come into the region near the wall with the fluctuating velocity possessed by the gas just outside the buffer region.

On this basis, calculations were made of the stopping distance and of the laminar sublayer thickness, assuming, as is customary, that $y^+ = 5$. These calculations showed that, for practically every run, the stopping distance was less than the thickness of the sublayer. The ratio of the stopping distance to the sublayer thickness, $S^+/5$, is shown in Figure 8. Thus, if the picture of a completely stagnant laminar layer is accepted, no deposition would have occurred in our tests because no particles could have diffused to within one stopping distance of the wall. It is therefore necessary to assume that some fluctuations do occur in the "laminar" sublayer. Lin, Moulton, and Putnam (7), who studied the transfer of materials of very low molecular diffusivity, came to the same conclusion. In order to correlate their results, they assumed that the eddy diffusivity in the sublayer is given by Equation 8. For the particles with which we are concerned, D_{BM} is negligible and the rate of transfer is given by

$$N = E_p \frac{dc}{dy} \quad (18)$$

If $E_p = E_g$, the rate of particle transfer through the sublayer is given by

$$N = \sqrt{\left(\frac{y^+}{14.5}\right)^3} \frac{dc}{dy} \quad (19)$$

Since the particles need to diffuse only to one stopping distance from the wall, the limits of integration are $c = 0$ at $y^+ = S^+$ and $c = c_s$ at $y^+ = 5$. Rearranging and integrating

$$c_s = \frac{(14.5)^3}{2V_{av}\sqrt{f/2}} \left[\frac{1}{S^{+2}} - \frac{1}{25} \right] \quad (20)$$

assuming that N_0 is a constant through the sublayer.

For the buffer layer, the eddy diffusivity is given by Lin as

$$\frac{\epsilon_s}{\nu} = \frac{y^+}{5} - 0.959 \quad (21)$$

Substituting in Equation 18 and integrating from $c = c_s$ at $y^+ = 5$ to $c = c_b$ at $y^+ = 30$, the edge of the turbulent core is

$$c_b - c_s = \frac{24 N_0}{V_{av}\sqrt{f/2}} \quad (22)$$

assuming that N_0 is constant through the buffer region.

For the turbulent core, the Reynolds analogy is used:

$$c_{av} - c_b = \frac{N_0}{(f/2)V_{av}^2} (V_{av} - V_b) \quad (23)$$

where, from Lin,

$$V_b = \text{gas velocity at } y^+ = 30 = 13.73 \sqrt{f/2} V_{av} \quad (24)$$

Adding Equations 20, 22, and 23, rearranging and substituting,

$$\frac{k}{V_{av}} = \frac{f/2}{1 + \sqrt{f/2} \left(\frac{1525}{S^{+2}} - 50.6 \right)} \quad (25)$$

This expression applies when S^+ is less than 5, i.e., when the stopping distance is less than the thickness of the sublayer. Curves calculated from this equation are plotted along with the experimental data in Figures 2, 3, and 4. In general, the theory agrees fairly well with the data except for the 0.8 micron particles for which only the trend of the theory is consistent with the results. As pointed out above, the greatest uncertainty in particle size was in these runs. Because of the extreme sensitivity of k to d_p , the theory would conform fairly closely to the data if 0.65 microns were used instead of 0.8 microns. When the stopping distance is small, i. e., when S^+ is less than about 1, Equation 25 reduces to

$$\frac{k}{v_{av}} = \sqrt{f/2} \quad \frac{S^{+2}}{1525} = \frac{\rho^2 d_p^4 \rho_p^2 v_{av}^4}{6.1(10)^5 \mu^4} (f/2)^{5/2} \quad (26)$$

This expression shows the extremely rapid increase of transfer rate with particle diameter and gas velocity when the stopping distance is less than the sublayer thickness.

If S^+ is between 5 and 30, the rate of transfer can be calculated by integrating Equation 18 between the limits $c = 0$ at $y^+ = S^+$ to $c = c_b$ at $y^+ = 30$ and using the Reynolds analogy for the core, giving finally

$$\frac{k}{v_{av}} = \frac{f/2}{1 + \sqrt{f/2} \left\{ 5 \ln \left[\frac{5.04}{S^+/5 - 0.959} \right] - 13.73 \right\}} \quad (27)$$

Only a few runs were made in this region. The data for the Lycopodium powder as shown in Figure 4 fall somewhat below the theoretical curve.

If the stopping distance is greater than the combined thickness of the sublayer and buffer regions, the transfer coefficient can be calculated using the eddy diffusivity for the turbulent core (12, p. 39):

$$\epsilon_g = \frac{\sqrt{f/2} V_{av} (R/R_0) y}{2.5} \quad (28)$$

and the assumption that the mass flux is linear with the radius

$$N = \frac{R}{R_0} N_0 \quad (29)$$

Substituting Equations 28 and 29 into 18, and integrating between the limits $c = c_c$ at $y = R_0$ to $c = 0$ at $y = S$, we obtain

$$\frac{k_c}{V_{av}} = \frac{\sqrt{f/2}}{2.5 \ln R_0/S} \quad (30)$$

where k_c is the transfer coefficient based on the concentration at the center of the duct. This can be converted to a coefficient based on average concentration by integration of the concentration profile, but such a refinement is probably not warranted.

Equation 23 is not valid near the center of the duct since ϵ_g does not equal zero at $R = 0$. For this reason, Equation 30 is not applicable as R_0/S approaches one. When the stopping distance approaches the duct radius, the suspension probably becomes extremely unstable. Equation 30 is plotted in Figure 9 with the data of Alexander and Coldren (1) for water droplets in a 1.86-inch pipe. The particle size was taken to be 27 microns as calculated by the authors from an empirical equation. In view of the many assumptions, the agreement of the theory with the data is good. As pointed out by

Alexander and Coldren, the transfer coefficients shown in Figure 9 are several times greater than the transfer coefficients of the common gases under the same conditions. This occurs, according to the theory, for two reasons: (1) The transfer coefficient is an inverse function of the diffusional distance which is less for particles than for gases, and (2) the particles need to diffuse only through the turbulent core where the eddy diffusivity is greatest.

Transfer coefficients calculated for the three regions from theory are shown in Figure 10 as a function of Reynolds number for 5 and 20 micron particles of unit density in a 2.5 cm. duct. The curves show the high sensitivity of the transfer coefficient to the velocity and particle diameter at low N_{Re} . When the Reynolds number is high, k is much less dependent on these variables; the relative lack of dependence of k on d_p at high N_{Re} may explain the agreement of the theory with the data of Alexander and Coldren who did not attempt to control the particle size.

VII. CONCLUSIONS

The rate of deposition of suspended particles from turbulent gas streams was studied as a function of particle diameter, particle density, gas velocity, and pipe diameter. The particles were much smaller than the scale of turbulence but sufficiently large not to exhibit Brownian motion. The phenomenon of turbulent deposition was found to depend on inertial effects with the rate increasing rapidly as particle diameter and gas velocity increased. The data were correlated by means of an analysis of the von Karman type, assuming that the particles did not have to diffuse to the wall but to within one stopping distance of the surface.

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NOMENCLATURE

c	=	concentration, particles or moles/cc.
c_s	=	concentration at $y^+ = 5$, particles or moles/cc.
c_p	=	concentration at $y^+ = 30$, particles or moles/cc.
c_{av}	=	average concentration, particles or moles/cc.
d_p	=	particle diameter, microns
D	=	duct diameter, cm.
D_c	=	scale of turbulence
D_{BM}	=	molecular diffusivity, $cm.^2/sec.$
f	=	friction factor, dimensionless
k	=	transfer coefficient, $cm./min.$
k_c	=	transfer coefficient based on concentration at center of duct, $cm./min.$
K	=	$3\pi\mu d_p$
L_t	=	distance from tube inlet to observation region, cm.
m	=	mass of particle
N	=	mass flux, particles or moles/ $(cm.^2)(min.)$
N_o	=	mass flux at wall, particles or moles/ $(cm.^2)(min.)$
N_{Re}	=	Reynolds number, $DV\rho/\mu$, dimensionless
N_{Re_x}	=	Reynolds number based on distance from duct entrance, dimensionless
N_{Sc}	=	Schmidt number, $\mu/\rho D_{BM}$, dimensionless
R	=	distance along duct radius
R_o	=	radius of duct
R_g	=	coefficient of correlation between gas velocities at different times
R_p	=	coefficient of correlation between particle velocities at different times

S	=	stopping distance
S ⁺	=	reduced stopping distance, $\frac{SV_{av}\rho}{\mu} \sqrt{f/2}$, dimensionless
t	=	time
T	=	time
v _g	=	instantaneous gas velocity
v _g ¹	=	root mean square gas velocity
v _p	=	particle velocity
v _{po}	=	velocity of particle at zero time
V	=	velocity of gas in axial direction at any point, ft./sec.
V _{av}	=	average gas velocity, ft./sec.
V _b	=	gas velocity at y ⁺ = 30
V ⁺	=	generalized velocity
x _g	=	gas displacement
x _p	=	particle displacement
y	=	distance from duct wall
y ⁺	=	$\frac{y V_{av} \rho}{\mu} \sqrt{f/2}$, dimensionless
E _g	=	eddy diffusivity of gas, cm. ² /sec.
E _p	=	eddy diffusivity of particle, cm. ² /sec.
μ	=	gas viscosity, g./ (cm.) (sec.)
ν	=	kinematic viscosity, cm. ² /sec.
ρ	=	gas density, g./cc.
ρ _p	=	particle density, g./cc.
τ	=	shear stress, dynes/cm. ²
τ ₀	=	shear stress at wall, dynes/cm. ²
ψ	=	inertial parameter, $\rho_p d_p^2 v / 18 \mu D_c$, dimensionless

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FIG.1 DIAGRAM OF EQUIPMENT

FIG. 2- DEPOSITION OF 0.8 MICRON IRON PARTICLES IN
0.54 CM. GLASS TUBE.

FIG. 3-DEPOSITION IN GLASS AND BRASS TUBES WITH VARIOUS COATINGS.

FIG.4-DEPOSITION IN 2.5 CM. GLASS AND BRASS TUBES WITH VARIOUS COATINGS.

FIG. 5-DEPOSITION OF 0.8 MICRON IRON PARTICLES NEAR ENTRANCE OF 0.58 CM. TUBE

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Figure 6
Photomicrograph of Iron Particles on Pressure Sensitive
Tape Showing Selective Deposition of Large Particles. (x 715)

Figure 7
Photomicrograph of Iron Particles on Millipore
Filter for Same Run as in Figure 6. (x 715)

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FIG. 8-RATIO OF STOPPING DISTANCE TO SUBLAYER THICKNESS.

#3

FIG. 9-DATA OF ALEXANDER & COLDREN (1) ON DEPOSITION OF WATER DROPLETS.

FIG.10-THEORETICAL CURVES FOR TRANSFER COEFFICIENT
FOR 2.5 CM. TUBE