OPERATING CHARACTERISTICS OF AN IMPINGEMENT TYPE DUST SEPARATOR

by

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Mass. Inst. of Technology
Cambridge, Massachusetts
June 1, 1946

Professor George W. Swett
Secretary of the Faculty
Mass. Inst. of Technology
Cambridge, Massachusetts

Dear Sir:

This thesis, entitled "The Operating Characteristics of an Impingement Type Dust Separator", is submitted in partial fulfillment of the requirements for the degree of Bachelor of Science in Chemical Engineering from the Massachusetts Institute of Technology.

Respectfully submitted,

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SUMMARY

The object of this report is to present the results of an investigation made on the operating characteristics and efficiency of an impingement type dust separator, operating in a low pressure system.

The separator studied consisted of a cylindrical glass chamber containing a pool of glycerine upon whose surface was directed a stream of dust-laden air. This air stream, carrying ammonium chloride smoke, entered the top of the chamber through a centrally located glass tube, the end of which was placed at a small but variable distance from the surface of the collecting medium.

The smoke was produced by the chemical action between ammonia and hydrogen chloride, and the particles were then carried by the fast moving air stream to the separator. Beyond the separator was located a two-section glass wool filter to remove the remaining smoke particles.

It was observed, during the course of operation, that the separator removed the larger, individually-visible particles, whereas the smaller particles, visible only as a thin cloud, were carried out of the separator in the air stream. Quantitative results

showed that when the ratio of the tube height above the glycerine to the tube diameter was decreased from 1.7 to 0.6, the efficiency of the separator increased from approximately 15% to 37%.

It is concluded that for the given system, as operated, the impingement type separator was effective in removing the larger size particles, but did not appear to separate from the air stream those particles of colloidal size.

In addition, the controlling factor of efficiency of dust removal for a given size distribution was found to be the separation factor, $\frac{V^2}{R}$.

INTRODUCTION

Industrially, there are several principle purposes in the removal of dust; namely, the elimination of a nuisance, improvement of product quality, elimination of a safety or health hazard, recovery of a valuable product, collection of a powdered product, or finally, the reduction of equipment maintenance. This last named purpose initiated the investigation which was carried out.

In a metallurgical process operating at very low pressures, it was realized that metallic vapors were condensing in the gas stream, and were being carried into the vacuum pump. The abrasiveness of these dispersoids necessitated a weekly reconditioning of the pump. Since any dust collecting device used in a high vacuum system must have as little resistance to flow as possible, the idea of impinging the high velocity metallic dust laden air on an oil bath was utilized as a means of removing the dust. It was found that the life of the pump was increased to six weeks.

At the time, no investigation was carried out to determine the operating characteristics of that impingement type dust seperator. Therefore, the purpose of this thesis was to study the operating characteristics of such a separator, and its efficiency in the removal of a dust from a high velocity, low pressure gas stream.

Many extensive studies have been made on the behavior of dust particles, and on many types of dust collectors, along both theoretical and practical lines. The following material summarizes the significant information which has appeared in the literature.

The behavior of dispersoids:

Solid matter suspended in a gaseous fluid is known generally as a gas dispersoid. (1) Such a dispersoid is the result of three general phenomena.

1. Condensation - The cooling of a diluted vapor condenses it to particles of its liquid or solid phase suspended in the gases of dilution. Such a phenomenon occurs when the hot gases over metallurgical furnaces are cooled and the metal vapor condenses to the solid phase.

2. Chemical action - The diluted gases of two react chemically to form a solid or liquid phase which remains suspended in the gases of dilution. An example is the reaction between hydrogen chloride and ammonia to form solid ammonium chloride.

3. Mechanical comminution - Large pieces of a substance are mechanically broken into very small particles, as the result of a grinding and/or pulverizing operation.

Condensation and chemical action phenomena as a general rule produce finer particles than mechanical comminution. The difference in size greatly influences the rate of fall of these particles in still air with no external force other than gravity acting upon them. A particle is pulled downward by gravity, but as it is accelerated, there is a retarding force due to a resistance to this movement by the gaseous medium. When these two forces are equal, the particle will move with constant velocity as shown by the following equations.

$$(1) \quad F = \frac{4}{3}\pi r^3 (\rho - \rho')g$$

where F = downward force
r = radius of the particle
ρ = particle density
ρ' = gas density
g = acceleration of gravity

$$(2) \quad R = 6\pi\eta r v$$

where R = retarding force
η = viscosity of gas
v = relative vel. of particle

equating (1) and (2) and solving for v,

$$(3) \quad v = \frac{2}{3} r^2 \frac{(\rho - \rho')g}{\eta} \qquad \text{(Stokes' Law)}$$

If the size of the particle approaches the mean free path of the molecules of the fluid medium, a correction factor must be applied. For particles very much greater than the mean free path of the gas molecules, which is 10^{-5} cm. at ordinary temperature and pressure, the bombardment by the gas molecules is evenly distributed over the surface of the particle, producing an even pressure over the surface. When particles are smaller than the mean free path, the contact of the gas molecules is not evenly distributed over the surface, resulting in the Brownian movement of the particle, In the latter case, the force of gravity has little effect. Particles of a size comparable to the mean free path tend to slip between the gas molecules; therefore, the value of R in equation ② is considerably diminished and the particles move at velocities greater than the values calculated by the use of Stokes' Law. (2)

The formation of larger particles as a result of condensation or chemical action depends upon the formation of nuclei and their growth as condensation continues. The vapor pressure increases with decreasing particle size. Therefore large particles would grow at the expense of smaller ones. (3) When the vapor pressure no longer has an effect, the particles may show a dipole nature and grow in chains. If no dipole tendency is shown, the agglomeration depends merely upon the actual collisions between the particles. Experimental evidence bears out the following relation: (4)

$$\frac{1}{n_2} - \frac{1}{n_1} = K(T_2 - T_1) \qquad (4)$$

where n = no. of particles in a given space at time T.

Therefore

$$-\frac{dn}{dT} = Kn^2 \qquad (5)$$

or, expressed in words, the rate of disappearance depends on the square of the number of particles. K has been calculated theoretically to be

$$K = \frac{4}{3}\frac{RT}{\eta N}\left(1 + A\frac{l}{r}\right) \qquad (6)$$

where R = gas constant
N = Avogadro constant
T = temperature
l = mean free path
r = radius of particle
A = a constant

Thus, it can be seen that as the factor $\frac{l}{r}$ increases, the rate of disappearance will also increase. Therefore, with extremely small particles, or in the case where the mean free path of the medium is greatly increased, the rate of agglomeration will be substantially increased. Experimentally, it has been found that the coagulation rate increases markedly with decrease in pressure; in one case, almost doubling when the pressure was dropped from 760 mm. to 400 mm. (5) Moreover, the size of the primary particles also increases with a decrease in pressure.

Methods of Separation

The separation of particles from a gaseous medium involves their movement through the medium by the application of a force. The force applied may be simply the pull of gravity, or it may be a centrifugal force, an electrostatic force, or an inertial force.

The settling chamber depends solely on the force of gravity to move the particle through the medium. Equation (3) expresses the velocity attained thereby. The velocity of a particle of unit density moving through air at 212°F is shown in the following table: (6)

radius of particle microns	velocity in./min.
104	620
100	573
74	313
44	111
10	5.75
1	0.0573
0.1	0.000573

The above table shows values where the assumption was made that there was no turbulence in the air. It can be seen that it would be impractical to separate particles smaller than 10 microns by this method.

In actual practice, the movement of air through chambers of large cross-section sets up turbulent areas which interfere with the steady downward movement of the particle. This can be alleviated by inserting horizontal shelves which shorten the necessary distance of fall, and also decrease the undesired turbulence.

The linear movement of the gases must be slow to allow the particles sufficient time to settle. Therefore, a very large apparatus is required for this type of dust separator. The two limiting factors on the use of the settling chamber are thus seen to be the size of particle to be separated and the available space for the settling chamber.

The cyclone separator utilizes the principle that a body moving in a circular path is acted upon by a force expressed by the following equation:

$$F = m \omega^2 R_1 \qquad (7)$$

Then, calling g_t the radial acceleration, and

$$g = \omega^2 R_1 \qquad (8)$$

we can substitute g_t in equation (3) to find the terminal velocity of the particle. The term "separator factor" is often used. This factor is the ratio of the radial acceleration to the acceleration due to gravity. The large increase in the force acting on the particle, and the corresponding increase in its velocity can be seen in the following table. (1)

Centrifugal Separating Force with
60 ft./sec. Tangential Velocity

radius of curvature	separating force
10 ft.	11 times gravity
5 ft.	22 " "
2.5 ft.	45 " "
1.0 ft.	112 " "
6 in.	224 " "
4 in.	336 " "
2.5 in.	538 " "
1.5 in.	896 " "

An inherent characteristic of a cyclone is a considerable turbulence due to the velocity of the swirling gases. However, the great increase in separating force makes separation far more rapid than in a settling chamber. Moreover, it occupies only a comparatively small space.

In the cyclone, a considerable power supply is necessitated by the change of the linear kinetic energy of the gas to rotational energy. The reverse cannot be carried out with any appreciable efficiency. It has been found experimentally that the pressure drop decreases with an increase in the dust loading.

This may be explained by the theory that as the dust moves from one layer of air to the next, it tends to transfer the energy of one layer to the other and thereby insures a more streamline flow. (7)

Double eddy cyclones have shown a 100% efficiency of removal of particles greater than 70 microns, and 60% efficiency of removal of particles of 5 microns. (7)

The inertia methods of separation have been used extensively in measuring the amount of dust in the atmosphere. A thin stream of dust laden air is directed upon a glass slide. The dust particles are carried through the film of air by their inertia and are held at the surface of the glass slide while the air bounces back. The particle experiences a force equivalent to that force which would act if the particle were introduced into a circular path of very small radius. Thus, the force would be of very high intensity, lasting for a very small time.

Calder and Fox have developed the impingement principle into a separator by placing strips of plate glass at an angle to the direction of flow, so that, the air stream is directed repeatedly on several glass surfaces. Because of the involved air movements, it is impracticable to mathematically analyze an impingement separator of this type; further, the operating factors will vary with each variation in design. Therefore the more convenient approach is the experimental. (2)

The <u>air filter</u>, which interposes a cloth or asbestos fabric in the air stream, utilizes the inertia and centrifugal principles as well as the simple straining principle. This is proven by the fact that particles much smaller than the openings in the cloth are trapped. When the particles are forced to change their direction while passing through the openings in the cloth, they experience forces of inertia which move them against the fibres of the cloth.

Filtering necessitates a high pressure drop in order to force the air through the pores of the cloth. This pressure drop continues to increase as the filtering process progresses, since the dust particles block the pores of the cloth.

Industrially, filtration systems will handle dust concentrations from .004 to 50 ounces per 1000 cubic feet at a velocity of 0.5 to 10 feet/ minute at the filter. However, for efficient operation a velocity of more than 3.5 feet/minute should not be attempted. (8)

Lastly, an electrostatic force can be employed to move the dust particles through the suspending medium. If a high electrical potential is maintained between a thin wire and a plate, there will be a corona discharge from the wire which ionizes the gaseous medium. If the wire carries a negative charge, the negative particles in the ionized gas will migrate to the positively charged plate. In their movement, they will contact the dust particles and give them a similar negative charge. These particles will also be attracted to the plate where they collect and can be removed. In brief, this is the principle utilized by the industrially sucessful Cottrell process.

In view of the fact that the system to be investigated operated at a low pressure and with a high velocity air stream, an impingement type separator was used, incorporating a liquid pool to entrap the particles. This design, in addition to its simplicity, offered an advantage over a filter separator which necessitates a high pressure drop not available in the given system, and an advantage over a settling chamber requiring large apparatus with additional mechanical difficulties due to the low pressures used. A wetted walled cyclone might prove to be an efficient separator; however, it too would introduce mechanical difficulties in design and construction. The Cottrell process for dust removal is ruled out by the fact that at pressures of 1 to 100 microns, a suitable charge cannot be maintained at the electrodes.

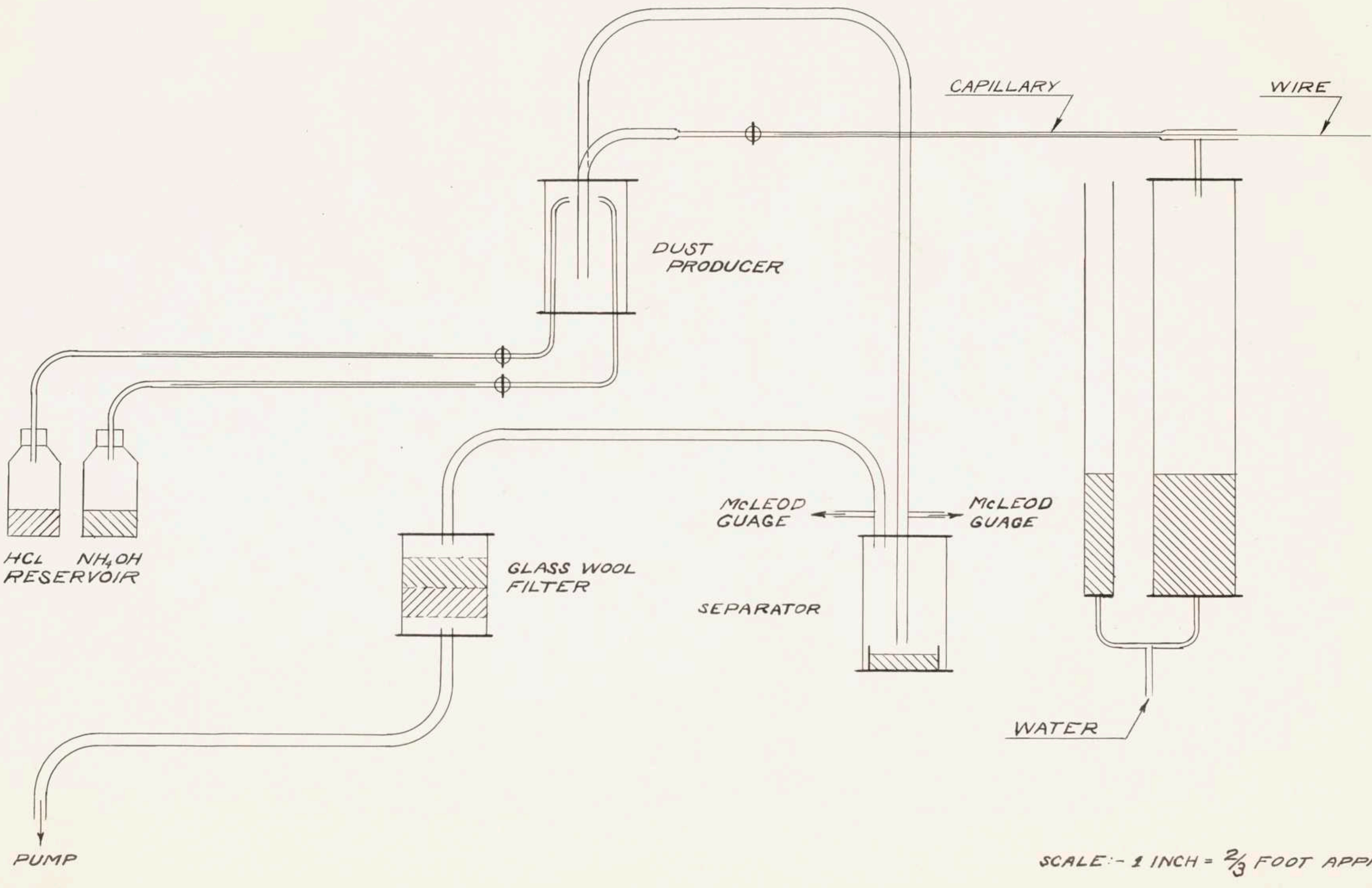
PROCEDURE

To obtain the desired information relative to the operating characteristics and efficiency of the separator, the following procedure was used. Smoke was generated by the chemical reaction between ammonia and hydrogen chloride vapors which were bled into a reaction chamber through capillaries from separate closed reservoirs, containing aqueous solutions respectively of 15% by weight of ammonium hydroxide and 36% by weight of hydrochloric acid. The air stream passed through the lower part of the reaction chamber and carried with it the ammonium chloride smoke and the excess reagents to the separator, where part of the smoke was removed. From there, the gas stream passed through the two-section glass wool filter to remove the remaining smoke, and then was exhausted through the pump.

The air rate was controlled by a length of wire in a capillary through which the air passed as it expanded from atmospheric pressure to the pressure of the system. At the entrance to and the exit from the separator, the pressure was measured by a McLeod guage connected to static pressure taps.

The following details of operation were carried out. After each run, the apparatus was cleaned and

FIGURE I
DIAGRAM OF APPARATUS



SCALE:- 1 INCH = 2/3 FOOT APPROX.

reassembled, using a given amount of glycerine in the separator, new glass wool filters, and given volumes of fresh solutions of reagents in their reservoirs. Then, when the length of open capillary was adjusted to give the desired air rate, the system was evacuated, and each reservoir in turn was evacuated to its boiling point. The two reservoirs were then opened to the system and, for a measured interval of time, smoke was produced and collected. During the run pressure readings were taken.

The apparatus was disassembled, the glycerine was washed from its well and diluted with water, the two sections of the glass wool filter were separately washed, the tube from the separator to the filter was washed and its washings added to the washings of the top section of the filter unit. To determine the ammonium chloride content of these washings, they were individually titrated against silver nitrate to a silver chromate end-point.

RESULTS

During each run, smoke production was not uniform. For the first two or three minutes it was possible to see the large particles impinge on the surface of the glycerine, and to see the thin cloud of small size smoke particles pass through the separator, as pictured in Figure II. After this initial

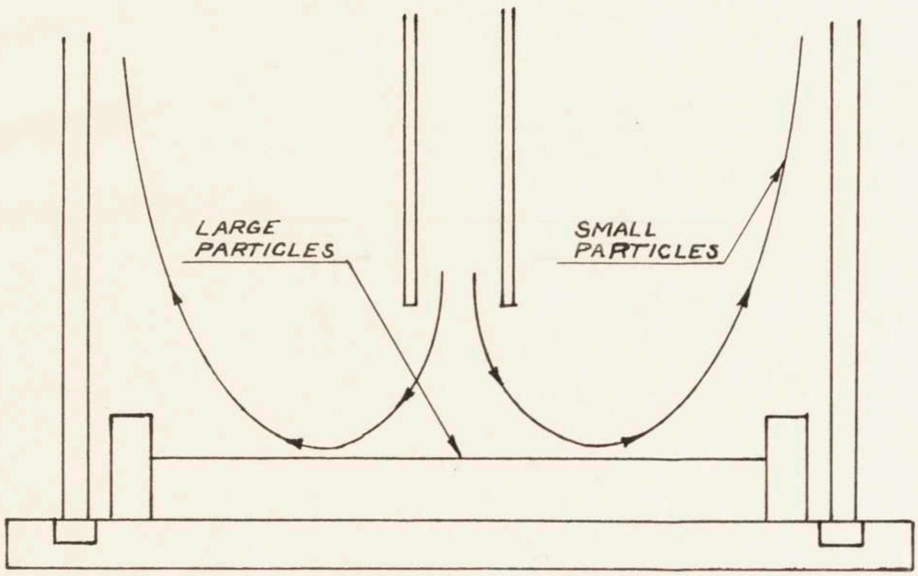


Figure II

production, the smoke was visible only spasmodically as the large particles were impinged on the surface of the glycerine. At the bends of the tube between the separator and the filter, ammonium chloride particles appeared and grew to a size much larger than the size particles that were observed in the separator. No dust was seen anywhere along the tube beyond the filter chamber.

Throughout each run during smoke production, the pressure in the system dropped continuously. However in earlier test runs, admitting only air, at constant pressure in the system, it was found that the linear velocity of the air did not vary greatly with the pressure, as shown in the following table.

Pressure * mm.	Air Rate ft./sec.
2.10	30.8
2.60	35.4
3.25	35.8
5.75	41.1

Calculations of efficiency of dust removal by the separator give the following results.

Run No.	h/d	E
1	1.7	12.2%
2	1.7	46.7
3	1.7	14.6
4	1.7	16.3
5	0.6	30.0
6	1.2	40.7
7	0.6	38.5
8	0.6	40.3

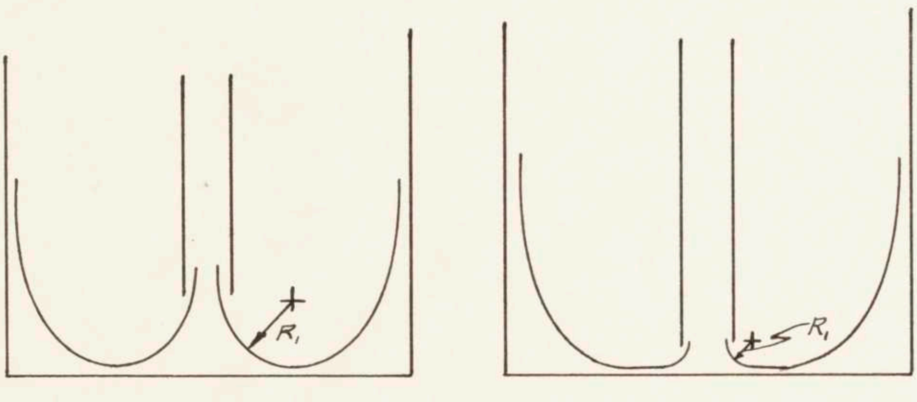
Little quantitative date was obtained due to the time spent in overcoming considerable difficulties involved in generating a satisfactory smoke. A discussion of the smoke producing problem is presented in Appendix I.

* A cold trap was not used with the McLeod guage. However, the pressure readings are not used quantitatively in the development of any conclusions.

DISCUSSION

A true index of efficiency of a dust separator should be expressed as a function of the particle size as well as a function of the other variable factors. The recorded efficiency in this report does not account for the particle size distribution, but only represents an over-all efficiency based on percentage removal by weight. Observation of the impingement process indicated that a large proportion of the larger size particles was removed, but a considerable portion of the small size particles passed through to the filter. Furthermore, it was observed that considerable agglomeration of dust particles took place in the tubing beyond the separator. If this agglomeration could be accomplished before the stream enters the separator, more large size particles would be retained, and the over-all efficiency would be increased.

Despite the fact that the particle size distribution is disregarded in the calculated efficiency, the data do suffice to warrant an evaluation of a change in efficiency when a change was made in one of the operating factors which would not affect the particle size distribution. It was found that by lowering the tube carrying the entering dust-laden air closer to the surface of the collecting medium, the efficiency of dust removal was increased. Assuming that this change did not affect the operating characteristics of the system, and had no effect on the particle size distribution, one can correlate the data with the visual flow pattern and point out that a desirable change has been made in the separation factor. This separation factor has been defined as the ratio of radial acceleration to the acceleration due to gravity, the former being expressed as $\frac{v^2}{R_1}$ where v is the velocity of the stream, and R_1 is the radius of the turn experienced by the flowing stream. A comparison of the flow pattern diagrams below indicates that by decreasing the distance



between the end of the tube and the surface of the collecting medium, the effective radius is decreased, and accordingly the separation factor is increased. It follows that, if this correlation is justified, a further increase in the separation factor would be achieved by an increase in the velocity. However, the available data do not cover a sufficient range of velocities to show the effect of a change in velocity upon the efficiency.

The above discussion has been developed from meager data, and more extensive data should be obtained to substantiate the conclusions. These data should include the results of tests using other smokes and dusts to justify the application of these conclusions to the general case.

The quantitative data presented show a fair consistency except for Run No. 2. This variation cannot be explained, but it is probable that the discrepancy was due to a change in operating conditions rather than to volummetric titration. For any given sample, the titration results can be closely checked.

CONCLUSIONS & RECOMMENDATIONS

In the design of an impingement type separator, it is recommended that the separation factor, as defined above, be the principle controlling factor in determining the efficiency of removal of dust of a given size distribution from a gas stream. This factor can be increased by decreasing the effective radius of the path of flowing gases at the point of separation, or by increasing the velocity of the gas stream. However, an unfavorable increase in pressure drop should be considered in evaluating the advantages obtained by increasing the separation factor.

In the use of an impingement type separator, sufficient time should be allowed for the particles to agglomerate before reaching the separator, in order that the weight percentage of large particles be increased for high efficiency of removal. This consideration was especially applicable with the NH_4Cl system. With other dust systems, it may be that further appreciable agglomeration could not be obtained.

It is therefore concluded that:

1. The controlling factor of the efficiency of dust removal is the separation factor.

2. The impingement separator effectively removes large size particles, but allows the colloidal particles to pass through.

3. The NH_4Cl particles continue to agglomerate for a finite period of time after they are formed.

It is accordingly recommended that:

1. The distance from the tube to the surface of the collecting medium be decreased, and the velocity increased, to a point where the efficiency desired is compatible with the permissable pressure drop.

2. A means be provided in the NH_4Cl system to allow further agglomeration of the particles before they reach the separator.

APPENDIX

APPENDIX I

Problems of Dust Production

Several methods of dust production were tried with little success. The first method was designed to take advantage of the low sublimation temperature of solid NH_4Cl at the low pressure of the evacuated system. The incoming air was directed upon the heated crystals to carry off the sublimed vapor into the system, where the vapors would condense to solid particles when the temperature was reduced. The NH_4Cl sublimed readily at approximately 200° C. However, the heat capacity of the incoming air was insufficient to affect the cooling, and the vapors were actually cooled by heat conduction through the glass walls of the tubing. The result was that the NH_4Cl condensed completely on the glass tubing, forming a solid dense deposit. Within twelve inches of the dust producer, the vapors were completely removed from the air medium.

It was proposed to form the NH_4Cl smoke by the chemical reaction between NH_3 and HCl. The first arrangement involving this principle consisted of bubbling the air through a 15% by weight aqueous solution of NH_3 before the air was passed through the capillary into the system. The HCl was bled directly into the reaction chamber from a closed reservoir containing a 36% aqueous solution of HCl. These vapors had to pass through a capillary between the aqueous solution and the reaction chamber. With this arrangement a very small quantity of dust was produced; in addition, most of it condensed on the reaction chamber wall opposite the opening of the HCl capillary.

The final arrangement consisted of bleeding in the NH_3 and HCl at the top of the reaction chamber from closed reservoirs of their respective aqueous solutiohs. The entrance and exit of the air stream were at the bottom of the chamber, thus allowing the vapors of NH_3 and HCl to mix and react at higher partial pressures since they were not yet diluted by the air. It also gave the particles some time to agglomerate before being swept away in the air stream. During the first two or three minutes of each run, there was a visible formation of smoke which gradually disappeared. A considerable amount of dust condensed on the walls of the reaction chamber.

None of these methods of smoke production was satisfactory entirely , especially from the points of view of constancy throughout a run, of control or size distribution. Further investigation should be carried out to design a smoke producing system which will remedy the defects of the present method.

APPENDIX II

SUMMARY OF DATA AND CALCULATIONS

Smoke Producing Runs

Run No.	l in.	t min.	h in.	k	W_G grams	W_{F1} grams	W_{F2} grams	E %
1	3	9	$\frac{3}{4}$	1.7	.0x109	.0x711	.0x071	12.2
2	5	12	$\frac{3}{4}$	1.7	.0x484	.0x533		46.7
3	7	10	$\frac{3}{4}$	1.7	.0x118	.0x565	.0x125	14.6
4	9	10	$\frac{3}{4}$	1.7	.0x253	.1x162	.0x141	16.3
5	3	8	$\frac{1}{4}$	0.6	.0x478	.0x646	.0x051	30.0
6	5	8	$\frac{1}{2}$	1.2	.0x231	.0x371	.0x169	40.7
7	7	9	$\frac{1}{4}$	0.6	.0x428	.0x582	.0x103	38.5
8	9	11	$\frac{1}{4}$	0.6	.0x312	.0x427	.0x035	40.3

The original complete data for these runs appears in the thesis notebook on pages 28 and 29.

Standardization of $AgNO_3$ Solution against NaCl

Dissolved 5.7 grams NaCl in 975 cc. of water to make a 0.1 normal solution of NaCl.

Dissolved 17.1 grams of $AgNO_3$ in approximately 975 cc. of water, and titrated samples of this solution against the 0.1 normal solution of NaCl.

Titration No.	ml. NaCl	ml. $AgNO_3$	normality of $AgNO_3$
1	10.05	11.10	0.0905
2	15.52	17.24	0.0901
3	13.76	15.31	0.0899
		average	0.09

Original complete data on page 25 of thesis notebook.

CALCULATION OF LINEAR AIR RATE

No.	Pressure	Length of open capillary	Rate of water rise	Air rate
	microns	in.	$\frac{1}{4}$ in/min	ft./sec.
1	2600	$5\frac{3}{4}$	4.75	35.4
2	2100	3	3.33	30.8
3	3250	8	6.0	35.8
4	5750	12	12.22	41.1

The air rate was calculated from the amount of air displaced by water at constant pressure in a closed reservoir.

$$\text{AIR RATE} = \text{volume of water} \times \frac{760}{p} \times \frac{1}{\text{area of tube}}$$

diameter of reservoir 3.75 inches

diameter of tubing 0.44 inches

based on Run #1,

$$\text{Air Rate} = \frac{\pi (3.75)^2 \ (4\frac{3}{4}) \ (760)}{(4)\ (4)\ (2600)\ (\pi/4)(1.75/4)^2\ (12)(60)}$$

$$= 35.4 \text{ ft./sec.}$$

SAMPLE CALCULATIONS

Based on Run No.5

	GLYCERINE	MAIN FILTER	FILTER CHECK
Total volume of washings	190	136	135
Volume titrated	19	14.5	14.0
$AgNO_3$ initially	14.77	15.63	16.06
$AgNO_3$ finally	14.29	14.81	15.69
ML. of .09 N $AgNO_3$ used	.48	.82	.37
Grams NH_4Cl	.0231	.0371	.0169

$$\frac{190}{19} \times .48 \times .09 \times \frac{53.5}{1000} = .0231$$

$$\frac{136}{14.5} \times .82 \times .09 \times \frac{53.5}{1000} = .0371$$

$$\frac{135}{14.0} \times .37 \times .09 \times \frac{53.5}{1000} = .0169$$

$$\text{EFFICIENCY} = \frac{.0231}{.0231 + .0371 + .0169} \times 100\% = \frac{.0231}{.0771} \times 100\% = 30.0\%$$

APPENDIX III

Table of Symbols

l = length of open capillary in air control, in inches

t = time length of run, in minutes

h = height of tube above surface of glycerine, in inches

W_G = grams of NH_4Cl in glycerine washings

W_{F1} = grams of NH_4Cl in main filter washings

W_{F2} = grams of NH_4Cl in check filter washings

k = ratio of tube height to diameter of entering tube

R_1 = radius of turn of air stream, in inches

d = diameter of tube, in inches

E = efficiency, as percentage

v = velocity of air stream, in feet/second

APPENDIX IV

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