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DUST CONTROL

Present and Future Design Considerations

By THEODORE HATCH

HARVARD SCHOOL OF PUBLIC HEALTH

FOR many years there has been a vague understanding of the relation between industrial dust and disease. Thus we find such names as "potter's rot" and "miner's consumption" antedating the relatively modern word "silicosis." In a few instances, notably in the South African gold mines, silicosis has been known for some time and has been accepted as a definite liability of the industry. In the United States also, certain sections of the mining industry were made aware of the dust hazard at an early date and a few sporadic studies were made in other industries, but with these exceptions workmen and employers alike were not generally cognizant of the danger of dust. This is especially true of the "new" industries in which the disease has not had time to establish itself as a tradition.

Although scientific methods for the detection of silicosis and requirements for its control have been developed, there has been no comparable progress toward its elimination. A review of state regulations of the dusty trades shows that they do not meet the present requirements of the problem and that satisfactory results cannot be expected with the methods of inspection and evaluation of control equipment now generally employed. Workmen's compensation acts did not originally provide for payment for incapacity resulting from occupational dust diseases, and at the present time only five states allow compensation for silicosis. Even in these one may say that it secured its place by default, for in no case is the disease specifically mentioned.

In the face of this unsatisfactory situation there has been a tremendous increase in the number of claims during the past few years. Most of these have been presented for settlement under the common law and thus the complicated and highly technical details of the problem have come before lay juries for consideration and judgment. Conflicting testimony has been given by medical and technical witnesses and the whole situation has become more confused as a result. It is evident that the *legal* aspects of the dust problem need revision and clarification, but regardless of the merits of settlement under common law compared with operation under a compensation act, the fact is that the *hygienic* and *economic* aspects of the problem can be settled only through permanent elimination of dust from industry. It is desirable, therefore, to inquire into the present status of engineering design of dust-control equipment.

PRESENT STATUS OF ENGINEERING DESIGN OF DUST-CONTROL EQUIPMENT

Textbooks on ventilation and engineering handbooks devote little or no space to methods of control of industrial dust, and in the technical journals, papers on fundamental engineering design of equipment are conspicuous by their absence. In a recent bibliography of the literature on pneumoconiosis, less than one per cent of the articles dealt with the engineering control of the disease. The *science* of dust control has not developed beyond the stage of trial and error, and the design of structures for the suppression of dust is based almost entirely upon empirical data together with one or two elementary formulas. The latter were derived from the generalized experience in a limited number of industries, such as woodworking, where conditions and requirements are not at all like those, for example, in a sand-pulverizing plant. Wide experience and good judgment are essential to the proper use of the scanty information that has been collected and systematized. Without attempting to minimize the importance of experience in engineering design, it is necessary to point out that most of the past experience obtained in the empirical design of dust-control equipment was not evaluated by means of quantitative studies of the actual reduction in dust. Hence, past experience does not necessarily furnish the proper guide for future design. In fact, recent surveys in certain industries, employing modern methods of investigation, have shown that existing equipment is in many cases inadequate.

Dust *control*, as practiced today, is to some extent the offspring of dust *collection*, but since they are opposite in purpose, the requirements of one are not necessarily like those of the other. Thus, manufacturers of dust collectors may guarantee collection of $99^1/_2$ per cent and in the production of a commercial powder this is entirely satisfactory, but it has no meaning in the performance of dust-control equipment. It is the escaping dust, not that collected, which is important, and guarantees of performance must be based upon permissible amounts of dust at the breathing zone of the workmen and in the "clean" air discharged from the equipment. For example, assume a safe limit of dustiness in the air discharged from a certain plant to be 1 mg per cu m or 0.000044 grain per cu ft and assume also a dust loading of 30 grains per cu ft. Under these conditions, which are not abnormal, the efficiency of dust "collection" must be 99.9985 per cent!

PRESENT STATE CODES INADEQUATE

Specifications in state codes for the design of exhaust hoods are commonly written in terms of the "static suction" to be maintained at the throat of the hood. Contrary to a widespread idea, suction per se has no effect in the capture of dust. The use of this index arises from the fact that it constitutes an approximate measure of the rate of airflow into a suction hood. This is true, however, only when the area of the throat and the size and shape of the hood are also given. In fact, as the following equation shows, these two factors are more important than the static suction, since the latter operates only at the one-half power

$$Q = 4000Af\sqrt{h}$$

where Q = rate of airflow at 65 F, cfm; A = area of throat, sq ft; h = static suction at throat, inches of water; and f = coefficient of restriction, which varies considerably with hood design.

Increasing mortality rates among workmen exposed to harmful dusts demonstrate the need for changing the regulations.

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In Wisconsin the new general orders issued by the Industrial Commission require hazardous plants to maintain atmospheric conditions below certain permissible standards established by recognized authorities. Thus structural details of control equipment are made secondary to results. Similar requirements have been incorporated in the proposed codes for other states. But with their adoption, it must be made clear that permissible values of dustiness are not absolute and may change as our knowledge increases. State requirements must therefore be kept flexible to allow for revisions dictated by new evidence and changes in "good practice." In order to facilitate this work and secure uniform requirements throughout the country, a national board is proposed whose purpose would be to review evidence and methods and prepare at stated intervals, for the assistance of state officials, standards of good practice for various dusty processes and industries.

The systematic correlation of actual results with the details of design, coupled with an understanding of the physical properties of dust and the laws governing its dispersion and behavior in the air, will provide a body of facts upon which to base the engineering design of equipment. Some of the fundamental factors are considered in the present paper.

PHYSICAL PROPERTIES OF DUSTS

Suspensions of dusts and fumes in the atmosphere, although possessing greater particle size, may be compared to a certain extent with colloidal systems. Gibbs has given the name "aerosol" to the dispersed system in which solid or liquid particles are dispersed in a gas. Aerosols differ, however, in their physical properties from hydrosols (dispersing medium a liquid). First, the settling rate of the dispersed material is very much higher, and second, molecular activity and therefore Brownian motion is greater. Consequently, the particles collide more frequently and the tendency toward flocculation is increased. Finally, aerosols differ in their electrical properties. Some particles carry positive charges, some negative, and some may be neutral; in a liquid medium, on the other hand, all particles generally have the same charge.

The formation of aerosols results from processes of dispersion including mechanical grinding, crushing and shattering, explosions, etc. Energy must be introduced to overcome the force of cohesion of the original material and the amount of energy required is roughly proportional to the area of new surface formed. The size of the particles produced depends upon the manner in which the shattering force is applied and also upon the geological structure of the material being crushed. Thus Jones[1] (1) has pointed out that in the South African "banket," the fibrous sericite, which occurs as a cementing material between the particles of quartz, is more easily broken down during drilling and blasting than the solid grains of silica and appears in the dust, therefore, in smaller sizes.

The physical properties of a material may be greatly altered from the original when it is finely ground and dispersed. The surface area and specific surface are enlarged many times and the rate of evaporation and solution as well as the adsorptive capacity are thereby greatly increased. Chemical activity also increases, since there is a larger proportion of unbalanced molecules lying at the surface. Aerosols differ also from one another in their physical properties, depending upon the degree of dispersion. It is convenient, therefore, to distinguish between different classes of aerosols. Gibbs's classification (2) is based upon the settling rate of particles in air:

(1) Dusts: Particles greater than 10 microns, settle with increasing velocity.

(2) Clouds: Particles 0.1 to 1.0 micron, settle with uniform velocity, according to Stokes's Law.

(3) Smokes: Particles 0.001 to 0.1 micron, do not settle in air.

Drinker (3) has modified Gibbs's classification and combined the idea of source of material with the degree of dispersion. It is more descriptive and conveys more meaning although it is physically less exact than Gibbs's grouping.

(1) Dusts: Particles 1 to 150 microns, generated by mechanical agencies such as crushing, grinding, drilling.

(2) Fumes: Particles 0.2 to 1.0 micron, resulting from chemical reactions such as distillation, complete and incomplete oxidation of metals.

(3) Smokes: Particles less than 0.3 micron, usually resulting from incomplete combustion of carbonaceous matter.

These classifications are valuable when considering methods of air cleaning and other problems related to dust control, since the method of treatment suitable to one class of suspension may be of no value in the case of another. Cyclones, for example, are valuable for the capture of coarse dusts, but despite the claims sometimes made for them, they cannot be depended upon to remove the fine material of hygienic importance.

MOTION OF PARTICLES IN AIR

Particles suspended in a gas are subject to two forces—external and internal. The former includes gravitation, centrifugal force, and electrical attraction. Internal forces result from molecular activity of the gas and from electrostatic charges carried by the particles.

External forces acting upon particles suspended in air cause them to move through the air with velocities that vary with the size, shape, and density of the particles, and with the density and viscosity of the air as well as with the strength of the external force.

The resistance to travel of spheres through a motionless gas may be written (4) $R = ka^n\rho\gamma^{(2-n)}V^n$, where a = radius of the particle; ρ = density of gas; γ = kinematic viscosity of gas; V = velocity of travel of particle; k = constant. In the region of streamline motion $n = 1.0$ and hence $R = ka\rho\gamma V$. This is the equation developed by Stokes for the resistance of small particles moving at low velocities. The resistance varies directly with particle radius and velocity. Large particles traveling at high velocities, on the other hand, set up turbulent motion. In this region $n = 2.0$; the resistance to motion becomes a function of the squares of velocity and particle diameter, and the viscosity effect is eliminated, thus $R = ka^2\rho V^2\gamma^0$.

Under the attraction of gravity, suspended particles fall with increasing velocity until the gravitational force $F = 4/3\pi a^3(\sigma - \rho)g$ is just balanced by the resistance R. At this point acceleration becomes zero and the settling velocity reaches a constant value which may be determined for the two forms of motion by the following equations

$$V = \frac{2}{9}\left(\frac{\sigma - \rho}{\rho}\right)\frac{g}{\gamma}a^2 \text{ (streamline)} \quad [1]$$

$$V = \left[\left(\frac{4\pi g}{3k}\right)\left(\frac{\sigma - \rho}{\rho}\right)a\right]^{\frac{1}{2}} \text{ (turbulent)} \quad [2]$$

Theoretically and experimentally, it has been shown that particles of quartz under approximately 75 microns in diameter settle according to the first equation, and that the particles must be greater than 2 mm in diameter to obey the equation of turbulent motion. Between these two limits is the region in which, according to Allen (loc. cit.), the resistance varies with velocity and particle diameter to the 3/2 power.

[1] Numbers in parentheses refer to bibliography at end of paper.

DISPERSION OF DUST INTO THE ATMOSPHERE

Dust particles, generated by whatever means, require energy for their dispersion from the point of origin into the surrounding atmosphere. Physically, this is provided in only two ways:

(1) Dynamic projection due to the kinetic energy of the particles themselves, imparted to them during their formation.

(2) Dispersion by means of air currents created by the operation of the dusty process.

The counter forces set up by the exhaust hood or other control device for the purpose of preventing the dispersion of dust must therefore be directed, in the first case, against the energy of the dust particles, and, in the second, against that energy which produces air currents around the machine. Since these forces of dispersion are quite different in form, it is clear that proper design of equipment depends upon an understanding of their relative magnitude and the manner in which they act. The first lends itself to approximate mathematical analysis which follows; the second depends upon the action of the dust-producing machine, and its evaluation requires careful analysis of the details of operation of the process.

DYNAMIC DISPERSION

A particle with mass m thrown off with an initial velocity V_0 possesses the kinetic energy

$$K.E. = \frac{1}{2} mV_0^2$$

and is resisted, as it travels through still air, by a force which varies with the type of motion and is determined by the equation

$$R = ka^n \rho \gamma^{(2-n)} V^n$$

Neglecting the force of gravity, the particle will travel along its path with a decreasing velocity until at a certain distance S the kinetic energy will be destroyed, i.e., its velocity will be zero. Thus

$$\int_{V_0}^{0} RdS = \frac{1}{2} mV_0^2 = \int_{V_0}^{0} -mVdV$$

Within the region of Stokes's law, $R = kV$, and therefore

$$\int_{V_0}^{V} dV = \int_{0}^{S} -k'dS$$

which, after integration, becomes $V = V_0 - k'S$. The value of k' ($k' = 3 \times 10^{-4}/a^2$ for spheres) varies inversely with the square of the particle diameter; doubling the size increases the length of travel four times for the same final velocity. For a 10-micron particle having an initial velocity of 5×10^3 cm per sec (10,000 fpm), $S = 4$ cm when $V = 0$.

If the particle travels with turbulent motion, however, the resistance varies with V^2 and we may write

$$\int_{V_0}^{V} \frac{dV}{V} = \int_{0}^{S} -k'dS$$

and from this

$$V = V_0 e^{-k'S}$$

Here $k' = 3 \times 10^{-4}/a$ for rounded bodies. The particle must travel an infinite distance to reach zero velocity but will, on the other hand, attain a low finite value of V in a finite distance. A particle with a diameter of 2 mm, for example, projected with the same initial velocity as in the previous example (10,000 fpm), will have a velocity of only 10 cm per sec (20 fpm) after traveling approximately 2000 cm or 67 ft.

These equations are not absolutely correct nor do they hold over the entire range indicated. The calculated values of S are therefore not exact. Nevertheless, they are correct in their relative orders of magnitude and to this extent they demonstrate an important principle, namely, that whereas large particles may be dispersed by dynamic projection through still air, microscopic particles, because of their relatively enormous surface area per unit volume, do not travel any appreciable distance by virtue of their own kinetic energy.

This principle is well illustrated by the action of a grinding wheel. Large particles are thrown off by centrifugal force and may be projected a considerable distance through still air, as the path of incandescent particles so clearly indicates. This force is not great enough, however, to disperse the fine particles. Some may be carried in the air stream created by the "drag" of the large particles and thus escape with them. To a greater extent, however, their dispersion is caused by air currents set up by the fan action of the rotating wheel. It follows, therefore, that an exhaust hood placed in the path of the incandescent large particles may not be sufficient, for this neglects the fine (and non-luminous) dust that is dispersed with escaping air currents around the periphery of the wheel.

The concept of the dual function of an exhaust hood, which arises out of the foregoing analysis, suggests that for successful dust control, three things must be done:

(1) The kinetic energy of the large particles must be destroyed. These particles are not important hygienically but they must be captured in order to prevent the escape of fine particles in the air stream created by their "drag." Their energy can be destroyed by means of barriers against which the particles impinge and lose their velocity, and the air currents induced by their motion can be dissipated by setting up counter currents in the zone of dust generation by means of air flow into the exhaust hood.

(2) Air currents created by virtue of the operation of the dusty processes must be eliminated through changes in the machine, or more generally by the application of suitable baffles and housing to prevent their formation.

(3) Air currents around the machine that cannot be eliminated must be changed in direction and made to flow into the exhaust system. This is accomplished by means of the potential gradient established between the suction opening and the surrounding air. Through hood design, the gradient must be maintained at the proper slope from the area of dust-production and at a minimum slope from the so-called ineffective areas in which no dust is produced. A knowledge of the aerodynamic characteristics of suction openings (5) is therefore essential to proper design.

Fundamental specifications for exhaust hoods cannot be established simply from a consideration of these factors. Experimental investigation must remain the most valuable aid to design. Nevertheless, the creation of a real science of dust control, which has been made necessary by the widespread industrial dust hazard, must be based upon physical laws. Empirical methods cannot be depended upon to relieve the heavy financial load that the dust hazard has placed upon industry.

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