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INDUSTRIAL DUST

Hygienic Significance, Measurement, and Control

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INDUSTRIAL DUST

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PREFACE

Control of the dust hazard in industry is the joint duty of the physician and the engineer. In the preparation of this book we have emphasized the cooperative nature of the problem and have devoted considerable space to such of the medical aspects as may help the engineer to understand the manner in which hygienic requirements affect engineering design and operation of dust-control equipment.

So far as possible, only the basic principles are considered. The book is written from the engineer's standpoint but we hope it will be of some value to physicians who wish to understand more fully the engineering aspects of the problem. Design of dust control apparatus is an engineering matter, but it is often the physician who finally appraises the success of the control system.

Unfortunately, current practice in the field of industrial hygiene permits the indiscriminate mixing of British and metric units. Thus, fans are rated in cubic feet a minute but dust particles are measured in microns. We do not support these inconsistencies but have merely followed the usual nomenclature and practice in this book.

Many friends and colleagues in this country and abroad have helped us with this second edition. At our request some of them read critically various parts of the manuscript and others supplied technical material. We extend to them our sincere thanks for their help.

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CHAPTER 1

PHYSICAL PROPERTIES OF DUSTS, FUMES, AND MISTS

Suspensions of finely divided particles in air in the form of fogs and mists are common natural phenomena. Not so well-known, because it is generally not visible, is the dispersed system of atmospheric dust that extends over the face of the earth. It is only during unusual climatic conditions, such as those of 1935 in the Middle West, when atmospheric dust concentrations reached staggering levels (Fig. 1), or in the more recent Donora, Pa.,

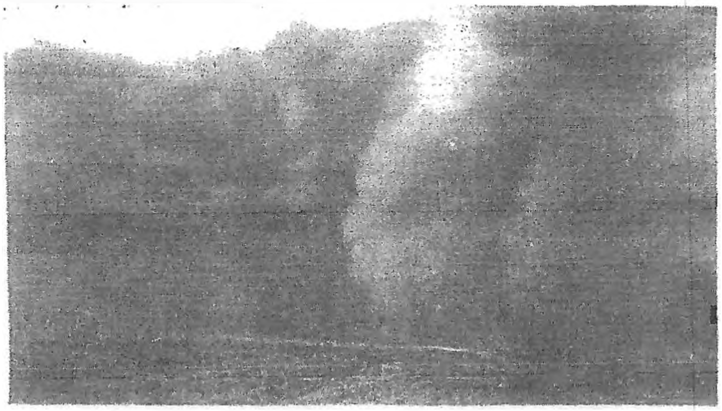

FIG. 1. Kansas dust storm, April, 1935. (*Courtesy Boyce.*)

incident (371), that the public becomes concerned with this phenomenon in a practical way. Within certain industries, on the other hand, contamination of the atmosphere with dust has long presented a problem, if not as a health hazard, then as a costly damaging agent against plant machinery or products. Even without producing measurable damage, dust constitutes a nuisance and creates poor working conditions.

In recognition of the hazards and cost of such contamination,

[1] Numbers in parentheses refer to corresponding items in the Bibliography on pp. 347–371.

the high levels of pollution of an earlier day have been largely reduced in the dusty trades. But the potential hazards remain, and the control of industrial dust continues as a never-ending battle. Beginning with empirical but common-sense measures, the dust-control program has now the benefit of considerable insight into the nature of dust hazards and is aided by quantitative methods for the measurement and evaluation of dust exposures. An understanding of the physical behavior of dust provides an increasingly sound engineering basis for the design of dust-control measures.

Some of the physical properties of dusts, fumes, and mists, which are important in a consideration of hazards, in the sampling and analysis of such materials, and in their control, are discussed in the present chapter. The subject is a large one and, in its theoretical aspects, has engaged the attention of physicists and chemists for many years. The application of the theoretical and experimental findings to the solution of practical problems, such as the subject of this volume, however, is relatively new. An outstanding contribution of a quarter century ago which brought together much scattered material was *Clouds and Smokes*, by W. E. Gibbs (183), now unfortunately out of print. This was followed in 1932 by *Smoke, A Study of Aerial Disperse Systems*, by Whytlaw-Gray and Patterson (442), and in 1943 DallaValle's *Micromeritics* (93) appeared. During World War II, as in World War I, extensive research added enormously to our understanding of the physical properties of finely divided matter in air, with direct and useful application to the study of industrial-dust problems. Much of this work has found its way into technical handbooks (245, 335). We shall have occasion to refer many times to these and other sources of basic information and shall be satisfied, here, to discuss the physical properties of dusts, fumes, and mists in only the briefest outline form.

Definitions. To all the various disperse systems in air, such as dust, fog, clouds, mist, fumes, and smoke, Gibbs (183) gave the general name *aerosol*, which is analogous to the accepted term *hydrosol* denoting disperse systems in water.

Dust is formed by reducing earthy materials to small size. Processes like grinding, crushing, blasting, and drilling produce dust particles of sizes from the submicroscopic to the visible, their composition being the same as that of the parent material.

Common examples are the mineral dusts derived from the disintegration of rock and the organic dusts like wheat and flour.

Fumes are formed by processes such as combustion, sublimation, and condensation. Typical examples are the fumes from burning lead or the zinc oxide produced from zinc vapor. Particle size is generally below 1 μ. In contrast to dusts, fume particles often flocculate vigorously.[1]

Smoke "presupposes a certain degree of optical density" (442). Generally it is of organic origin, but it may include systems consisting "of particles of low vapor pressure which settle slowly under gravity." We shall use the word with reference particularly to systems that are organic in origin, such as the smoke from burning tobacco, wood, oil, or coal. In general, smokes are characterized by a particle size below 0.5 μ.

Mists or *fogs* are formed by the condensation of water vapor upon suitable nuclei or by the atomization of liquids. Particle or droplet size varies widely depending on the conditions prevailing.

General Properties of Dusts, Fumes, and Mists. Disperse systems of dusts or other finely divided matter in air occupy a position with respect to size properties between the colloidal and the macroscopic regions. The particles are larger than those in colloidal systems; yet they are small enough to exhibit some of the properties of colloids and also to have properties not possessed by large masses of the substances from which they are generated.

When a solid or liquid is broken up into finely divided particles and is dispersed in the air, two important changes take place: (1) the surface area is greatly increased, and (2) the space occupied by the dispersed material is expanded many times over the volume of the original mass. Thus, if 1 cc of quartz is crushed into particles of 1 cu μ in size, there will be 10^{12} particles with a total surface area of 6 sq m as compared with 6 sq cm for the original block. Assuming a dust concentration of 100 million particles per cubic foot of air, the 1 cc of material will be dispersed in an air volume of 10,000 cu ft.

The effect of these changes is to intensify the chemical and physical activity of the material. The rate of oxidation is increased so much that substances like soft coal and aluminum

[1] It is usual to speak of acid *fumes* as denoting a mixture of gas and mist. Throughout this book, however, we shall use the word to designate only solid particles.

powder burn in air with explosive violence. Rates of evaporation and solubility are also increased, and the phenomena of adsorption and electrostatic activity are intensified. The adsorption of a gas film on the particle surface may accelerate or retard chemical reactions, and it also interferes with physical phenomena such as wetting. Since the physiological effect of dust particles always is intimately associated with their physical and chemical activity, small particles generally are of more physiological importance than large ones.

Similarity between Dusts and Liquids. Owing to the large amount of air adsorbed upon the surfaces of fine dust particles, a mass of such particles assumes some of the properties of liquids and gases. The mass can be compressed, and it splashes like a liquid when being carried in a pail. It can be poured through a pipe, and ripples are formed when a stone is dropped into a tank of dust.

Dust can be "distilled" by passing air through it; the amount carried over varies with the air velocity. A fixed rate of air flow will "evaporate" a constant amount, and the air will become "saturated." When the air speed reaches a certain critical value, the whole body of dust will be carried over, *i.e.*, the dust "boils." In these examples air velocity corresponds to temperature (293).

PARTICLE DYNAMICS

Like any other body, a microscopic particle is attracted toward the earth, but because of its relatively great surface area per unit of mass and the consequent high air resistance, an air-borne particle does not fall with increasing velocity according to the ordinary law of gravity. Almost immediately after it starts to fall, the air resistance imposed upon the particle balances the gravitational force, thus preventing further gain in speed. The particle then settles at its constant terminal velocity, which for microscopic particles is low, being measured in centimeters and even millimeters per hour. As a consequence, dust suspensions in air have considerable stability and may persist for long periods. Because of the great air resistance it is difficult to project microscopic particles through air and equally difficult to remove them from the air. In a sense, the finest particles become a part of the air itself.

The dynamic properties of microscopic particles are thus of the greatest importance in a consideration of dust hazards and their control. The characteristics of dust dispersion into the air, the spread of dust away from its source of generation or release, the control of dusty processes, and the problems of air cleaning are all intimately related to the dynamic behavior of air-borne dust. Physiologically, these properties are also of major concern for they largely determine the depth of penetration and degree of retention of inhaled dust in the respiratory tract and, hence, limit the lung-dosage rate in relation to air concentration and with it the dust hazard.

General Law of Resistance. Resistance to the travel of a particle through air varies with the size and shape of the particle, with its velocity, and with the fluidity of the air. These factors are combined in the following general equation:

$$\mathcal{R} = \frac{C\rho A u^2}{2}$$

where $\mathcal{R}$ = resistance
C = coefficient of resistance
A = projected area of particle
u = particle velocity relative to air
ρ = air density

The drag coefficient C is not constant for all conditions of motion but varies systematically with the dimensionless Reynolds number $\mathrm{Re} = ud\rho/\mu$, μ being the viscosity of the air and d the particle diameter. C also varies with the shape of the particle, the effect being different for different values of Re.

The relationship $C = f(\mathrm{Re})$, further simplified from the curves of Lapple and Sheppard (275), is shown for spheres in Fig. 2 for a range of Re from 10^{-4} to $>10^5$. The relationship has been divided into three zones according to the nature of dependence of C upon Re. For high values of Re ($>10^3$), C is reasonably constant and for spheres has an average value of 0.44. This is the zone of turbulent motion where the viscosity of the air has no effect. For this region, resistance varies with the squares of particle diameter and velocity (Newton) thus:

$$\mathcal{R} = k\rho d^2 u^2$$

For spheres, $k = 0.44 \times \pi/8$. When $\mathrm{Re} < 3.0$, however, C varies inversely with Re:

than in dry weather and also from the fact that the greater air movement on dry days carries away more dust.

Supersaturating the atmosphere with moisture does have a noticeable effect upon suspensions of dusts and fumes owing to the fact that the particles act as nuclei upon which the moisture condenses. The application of live steam in air cleaning is more effective than a water spray. In Figs. 9 and 10 is shown the rapidity with which clouds of zinc oxide and tobacco smoke can be cleared up with steam. In contrast to this, Warren (436) found the efficiency of water blasts for cleaning mine air to be only 62 per cent. During dry drilling, external water blasts do not improve conditions, according to Harrington (206), while Gray (188) states that water blasts and sprays fail to bring down the really fine dust.[1]

OPTICAL PROPERTIES

The presence or absence of suspended dust in the air is easily demonstrated by directing a beam of light through a darkened room containing the dusty air. The beam will not be revealed unless there are suspended solid or liquid particles to reflect the light. This test, which was first used by Tyndall in his classic studies of atmospheric pollution, is one of great sensitivity.

The optical behavior of an aerosol varies with the nature of the suspended material, such as its transparency and shape, but it is influenced to a greater degree by the size of particles in the suspension. Distinction may be made in this connection between two classes of particles: those larger than the wavelength of light, which reflect and refract light according to the general optical laws, and a second group containing particles sensibly smaller than the wavelength of light. These particles scatter light in all directions with an intensity that varies with the wavelength of the light; the light is polarized to a considerable extent. The light scattered by large particles is also polarized to some extent in a plane perpendicular to the incident beam.

Particles Larger than the Wavelength of Light. Tolman (414) has shown that the intensity of light reflected by particles larger than 0.6 to 0.7 μ is given by the equation

[1] See Chap. 16 for a discussion of spray-type air cleaners.

$$I = \frac{kc}{d}$$

where I = intensity of reflected light
c = concentration (weight) of dust per unit volume
d = particle size

Since

$$c = \frac{\pi}{6} d^3 \sigma n$$

where σ = density of dust particles
n = number of particles per unit volume of the suspension

we may write

$$I = k'nd^2$$

where k' includes several physical constants pertaining to the dust. Thus, the strength of the Tyndall beam varies directly

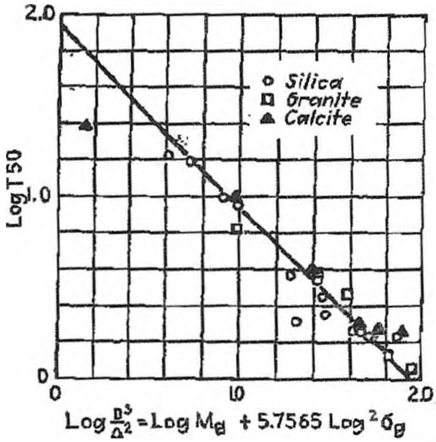

FIG. 11. Relation between tyndallmeter reading and particle size expressed in terms of M_g and σ_g. *(Courtesy J. Franklin Inst.)*

with the surface area concentration of the particles in the suspension. For equal weight concentrations per unit volume, however, the strength of the beam varies inversely with size (Fig. 11).

Particles Smaller than the Wavelength of Light. In this region the intensity of the beam varies, according to Rayleigh, with concentration, size, and wavelength of the incident beam in the following manner:

$$I = \frac{knd^6}{\lambda^4} = \frac{k'cd^3}{\lambda^4}$$

where λ = wavelength of light

Again, the intensity varies with the concentration of dust in the suspension. It is also influenced to a considerable degree by the wavelength of light; red rays, for example, are scattered with only one-twelfth the intensity of the rays at the short end of the spectrum. Conversely, the long rays are transmitted through a suspension to a greater degree than the violet rays. Hence, the Tyndall beam developed by minute particles appears blue in color when viewed at right angles and red when examined from the end. This explains the blue color of the sky, which is produced essentially by light scattered by gas molecules and minute particles, and the red at sunset, which comes to us by transmission through the dust atmosphere near the earth's surface.

For equal weight concentrations, the intensity of the scattered light increases rapidly with particle size to a maximum in the region corresponding to the wavelength of the incident beam and then decreases less rapidly with a further increase in size, the exponent of d changing from 3 to -1. This is nicely shown in terms of the variation in strength of the transmitted beam with particle size (407) in Fig. 12.

A more complete theoretical treatment of the laws of light scattering by small particles was developed by Mie (313). During World War II, this was employed extensively in the optical study of homogeneous aerosols by La Mer and associates (245) who developed methods for determination of particle size and concentration, based upon the selective scattering and transmission of light of different wavelengths and the variation in degree of polarization with particle size. The method is limited, however, to the study of particles of uniform size and has little application to the study of heterogeneous industrial dusts.

Obscuring Power. The intensity of a light beam passing through a dust suspension when viewed on end decreases with an increase in the distance from the light source as well as with an increase in dust concentration. Simon and his coworkers (389)

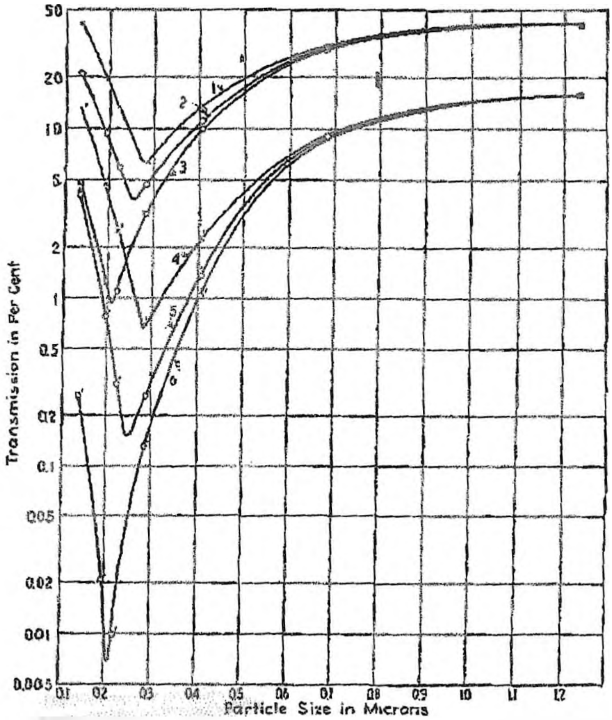

FIG. 12. Variation in light transmission with particle size. (*After Stutz, courtesy J. Franklin Inst.*)

have shown by theoretical considerations, assuming a suspension of opaque spherical particles of uniform size, that the intensity of light changes according to the logarithmic equation

$$L = L_0 e^{-n(\pi/4)d^2 l} = L_0 e^{6ml/4\sigma d}$$

where L and L_0 = intensities of incident and emergent beams, respectively

l = length of path between points where L_0 and L are measured

n = number of particles per unit volume of air

m = weight concentration of dust per unit volume of air

σ = density of material of which the dust is composed

Written in another way, this relationship shows that the *percentage reduction in light* for a given column of the dust-laden air is constant, regardless of the intensity of the incident beam, and that the percentage value varies directly with the number of particles, length of path, and square of particle size.

The correctness of this theoretical equation was demonstrated by Simon (389), who describes a method of measuring the relatively heavy concentration of dust in blast-furnace gas based upon this equation.

It is frequently suggested that this phenomenon could be used as a simple method for determining the concentration of dust in an industrial establishment. The application of the above equation to a practical problem, however, indicates the fallacy of this contention. Assume a concentration of 10 million particles per cubic foot of air (350 particles per cubic centimeter) with a uniform diameter of 2 μ, and determine the distance l necessary to reduce the light intensity only 5 per cent, *i.e.*, from 100 to 95. Entering these values in the above equation, we get

$$l = 47 \text{ m}$$

Obviously, this distance is too great for practical use, although to be effective any dust recorder must be sensitive to a degree as close as 10 million particles per cubic foot.

CHAPTER 2

EFFECTS OF DUSTS AND FUMES UPON MAN

Exposure to dusts can produce several distinct types of di ability: (1) the pneumoconioses are caused only by dust inhal tion; (2) systemic toxic effects are produced as the result either breathing or swallowing of certain dusts such as lead an manganese; (3) metal-fume fever is caused by inhaling certai metallic oxide fumes; and (4) an allergic reaction, as typified b hay fever, is the direct result of breathing pollen or other organ substances. Dust inhalation is the usual cause of disability; onl in the case of a few dusts are there other modes of entrance.

Respiration and Dust Inhalation. The lungs are nonsym metrical bilateral structures encased in a rather elastic cavit the chest, and they communicate with the nose and mout through the trachea, or windpipe. The left lung has two divi sions, or lobes, and the right lung has three; the right lung i about 12 per cent larger than the left. (Fig. 13)

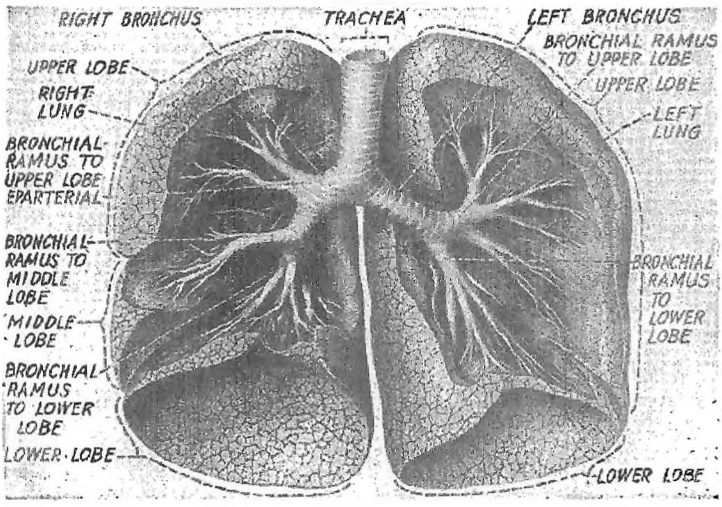

FIG. 13. Lungs, bronchi, and trachea. (*After Sobotta and McMurrich.*)