DEVICES AND METHODS FOR HIGH EFFICIENCY INDUSTRIAL PARTICULATE EMISSION CONTROL

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ABSTRACT

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Control of particulate emissions from industrial processes has long been in the forefront of air pollution problems facing industrialized countries. The choice of basic processes for the effective removal of particles, in the micron and submicron range from gases is limited to filtration, high energy scrubbers and electrostatic precipitation.

The various design approaches and methods adopted in the fabrication and installation of such emission control devices are reviewed and assessed in light of the current stringent environmental standards. The particle and gas properties which influence greatly the design and performance of control equipment are identified and discussed. Baghouses and high energy venturi scrubbers are the only types of filtration and scrubbing equipment discussed in this report. The theory of electrostatic precipitators as it applies to the collection of particulates from industrial stack exhaust gases is reviewed, and the basic precipitator size and electrical parameters are individually analysed and related to particle and flue gas properties.

The problem of high resistivity particles, which is one of the most common causes of poor precipitator performance is dealt at length.

Selection, evaluation and application criteria for control devices, is detailed with respect to present needs and future industrial requirements.

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NOMENCLATURE

NOMENCLATURE

x	particle diameter, μ
u	logarithm of particle diameter, $\ln x$
$\bar{x}g$	mean geometric diameter, μ
$\bar{u}$	logarithm of the mean geometric diameter, $\ln \bar{x}_g$
σ_g	geometric standard deviation, μ
σu	logarithm of geometric standard deviation, $\ln \sigma_g$
Pc	amount of pollutants collected by the control device.
P_p	amount of pollutants entering the control device
Po	amount of pollutants escaping the control device
η	efficiency, dimensionless
DF	decontamination factor, dimensionless
ΔP	pressure drop, cm of water, (inches of water)
U_G	gas velocity relative to duct, cm/sec, (ft/sec)
U_L	liquid velocity relative to duct. cm/sec. (ft/sec
Q_L	gas volumetric flow rate, m^3/sec, (ft^3/sec)
Q_G	liquid volume flow, m^3/sec, (ft^2/sec)
V_c	voltage required for corona initiation, volts
m	wire rouphness factor, dimensionless
b	electrode spacing, m, (f)
a	radius of corona wire, m, (ft)

q	particle charge, C
q_s	saturation particle charge, C
N_o	free ion density, number/m^3, (number/ft^3)
e	electronic charge, C
μ	micrometers
μ	mobility of ion, m^2/V-second
E_o	permittivity of free space, C^2/J-m)
C	effective velocity of ion cluster, m/second, (ft/second)
α	particle radius
A	total collecting surface area, m^2, (ft^2)
V	gas volume flow rate, m^3/second, (ft^2/second)
ω	particle migration velocity, m/second, (ft/second)
λ	mean free-path of gas molecules, m, (ft)
R	dust resistivity (Ω.m)
V	voltage across the dust layer, V
j	current density through the dust layer, A/m^2, (A/ft^2)
ℓ	dust layer thickness, m, (ft)

CHAPTER I

INTRODUCTION

CHAPTER

INTRODUCTION

1.1 THE CASE FOR PARTICULATE CONTROL DEVICES

Industrial plants such as fossil fuel power generators and raw material processing installations discharge large volumes of gaseous emissions into the atomsphere. These exhaust streams contain in suspension a variety of particulates which are a direct byproduct of the process performed in each particular installation. The term suspended particulate or simply particulate, refers to any matter dispersed in the air consisting of solid or liquid particles ranging from less than 1.0 μ to more than 100 μ [1].

The uncontrolled dispersion of particulates into the environment, produces a cumulative contamination of the atmosphere and thereby affects adversely the evolution and quality of life. For example, it has been shown that the health hazard to people exposed to high levels of air pollution become significant in heavily industralized areas where it is estimated that up to 350 kg of pollutants may be emitted per capita per year [2,3].

In order to preserve the quality of the enviroment, a number of local and regional regulations have been enacted [4,5] which attempt to legislate maximum acceptable pollution levels for each type of industrial process. These regulations attempt to control the discharge

of particulate matter directly into the atmosphere by stipulating the relative concentration of each element depending on size and chemical composition. Manufacturing and service plants which do not satisfy these regulations are obliged to process the exhaust gases, through devices which separate the particulates from the non-deleterious gaseous discharge.

Several different types of particulate control devices are available commercially to handle the large range of chemical elements and particle size which arise in industry. In this report, the three main types of air quality control equipment currently in use will be covered. These are generally classified into fabric filters (baghouse systems), wet scrubbers, and electrostatic precipitators [6]. Mechanical separators have also been employed in this field with limited success. Clearly, industrial control devices must be capable of separating solid particles of submicron size from large volumes of frequently corrosive gas flows at elevated temperatures. This function must be accomplished in an efficient and reliable manner over the complete range of operating conditions. The insertion of a control device in the exhaust cycle represents an additional manufacturing cost and therefore, it is essential to perform the removal of particulates from the carrier gases as efficiently as practical.

The variety and complexity of industrial processes usually precludes the routine application of a single particle collection method. Each gas

cleaning problem needs to be analyzed individually to establish the performance specifications appropriate to a given set of operational requirements. Once this has been done, it remains to select equipment which will achieve the particle separation function necessary to comply with the enacted regulations at the lowest combination of capital and operating costs.

1.2 GENERAL TYPES OF CONTROL DEVICES

Particulate emission control devices are essentially collectors which are broadly classified as Mechanical, Fabric Filters (Baghouses), Wet Scrubbers and Electrostatic Precipitators.

Mechanical collectors such as Cyclones and Baffled chambers are normally used on coarse heavier materials. They are not very efficient in the removal of particles below 10 μ in size and for this reason their main application is in conjunction with other more sensitive control devices.

Fabric filtration is a reliable and efficient method for removing small size particulate matter from gas exhaust streams. Fabric filters come in many types such as Fabric-baghouses, Fibrous Beds and Granular Beds. These devices function by trapping the particles on the dirty-gas side of the fabric while allowing the gas to pass through the interstices between the woven threads for the fabric.

Scrubbers utilize a liquid, usually water to remove contaminants in either vapor or fine particulate state from a gas stream. The main types are spray, centrifugal, packed bed and venturi scrubbers. These devices accomplish the desired separation via the entrapment of the particles into liquid droplets.

In electrostatic precipitators the entrained particulate matter is separated from the gas stream by first charging the particles to a high negative (or positive) voltage, precipitating them on to grounded collecting electrodes and then discharging the agglomerated particles into a hopper. Electrostatic precipitation differs fundamentally from the other control methods in that the separation forces are electrical and are applied directly to the particles themselves, rather than indirectly through the gas stream.

All control devices are designed on the basis of mathematical relationships, derived in part from the theoretical principles underlying the control mechanisms and in part from empirical data accumulated from tests of pilot and full-scale installations. While theoretical relationships are useful in providing an insight into the various processes, they tend to become rather cumbersome in engineering applications. The wide range of operating conditions, particle characteristics and process requirements make it particularly difficult to develop control devices on the basis of theoretical models alone. In practice the design of such systems is based primarily on experimental and performance data. Usually, the design

evaluation process includes consideration of the control efficiency, capacity, size, pressure drop, power consumption, utility requirements, operating reliability and component life. However from the view point of environmental protection and compliance with the regulatory limitations control efficiency remains the most important performance parameter.

1.3 LEGISLATIVE AND REGULATORY IMPACT

The environmental side effects of science and technology have increased public awareness of the importance of protecting our ecosystem. In this context individual states and municipalities have implemented and enforced the laws which have been promulgated to control the permissible level of emissions in various industrial processes.

The introduction of governmental requirements for air pollution control has injected a new factor into the level of particulate control imposed on industry. The required collection efficiency of the control device to meet air pollution requirements has been increased progressively from the nominally 90 per cent collector for economic purposes to a level more than 99 per cent. These standards have evolved gradually and are continuously updated to respond to the changing needs of our society. Presently, the Emission Standards and Engineering Division of the U.S. Environmental Protection Agency (EPA) is currently studying the effect and control of fine particulate (less than 3 μ down to 0.01 μ) to best determine how to set standards for this size of

particulate [7].

An up-to-date history of air quality legislation, Federal, State and Local standards, national distributions of air pollutants, air quality control costs, and a selection of recent publications related to air pollution may be found in [1,8,9]. For Canada the "Clean Air Act" [10] provides the basis for the federal government's air pollution control activities.

The increasingly stringent emission regulations, in the past few years, have led to accelerating research programs, and control device design improvements, far superior to any unit that could have been built 10 years ago. Efficiencies and availability records not considered possible a few years ago are now routinely achieved. Some of the factors responsible for the superiority of modern precipitator systems are: far more sophisticated mathematical techniques for predicting device performance; superior construction materials; computerized data banks of technical information based on 50 years or more of experience in building pollution control devices; and availability of high-quality auxiliaries such as flues, dampers and handling systems.

It should also be pointed out that the potential economic impact of the governmental ambient air quality standards for fine particulates is of a great magnitude [11]. According to the 1973 costs of air pollution abatement to U.S. industry in terms of 1970 dollars were about $8.5 billion. The oil industry alone spent $737 million for

quality improvements that year. Estimates indicate that these costs, will rise to $20 billion for the year 1975 [12], and over the period of 1973-1977 the amount of $42 billion will need to be expended if the emission reductions are to be achieved as required under the relevant regulations [13].

CHAPTER II

CHARACTERISTICS OF INDUSTRIAL STACK PARTICULATES

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2.1 GENERAL

It is well recognized that no universal gas-cleaning method exists which will satisfy the full range of industrial requirements and conditions. The selection of a particular method depends on many technical and economic factors, among which the physical and chemical properties of the particulate matter are the most fundamental. For example, coarse dust particles are easily separated by centrifugal collectors, whereas, fine dusts, fumes, and smokes require the use of filtration, scrubbing, or electrical precipitation. In view of the multitude of processes and equipment that need to be covered, no comprehensive guide for the selection of control devices has been developed.

Gas-cleaning equipment, which represents the bulk of control devices employed at present, have been studied by several investigators. The performance and efficiency of this type of equipment is determined primarily by the characteristic properties of the particulates involved and the nature of the gas flow itself. These properties include particle size distribution, particle structure, density, composition, concentration, electrical conductivity (in electrostatic precipitation), and agglomeration qualities. Gas properties, such as temperature, moisture content, total

gas flow, and chemical corrosiveness are a further set of parameters which must be taken into consideration. Flodin [14] has studied the performance of gas-cleaning equipment with respect to the basic particle properties outlined above. Collection efficiency as a function of particle size, shape and density has been reported in [15].

Data on particle size for some typical industrial dispersoids are given in Table 2.1 . The techniques employed to determine the actual size and the methods developed to characterize the physical dimensions of particulates are discussed in the following section.

2.2 PARTICULATE SAMPLING AND MEASUREMENT TECHNIQUES

The detection and monitoring of particulates is a highly specialized branch of analytical chemistry, and a complete description of the subject is beyond the scope of this report. However, since stack gas characteristics influence in a major way the design, choice and efficiency of control equipment, a brief summary of sampling and measurement techniques will be given.

Stack emissions may be estimated indirectly from what is generally known about a source or they may be obtained by direct testing of the source. Detailed source sampling and monitoring is practical for large individual sources such as electric power stations and manufacturing plants. Standard procedures have been developed for the collection and analysis of various types of industrial

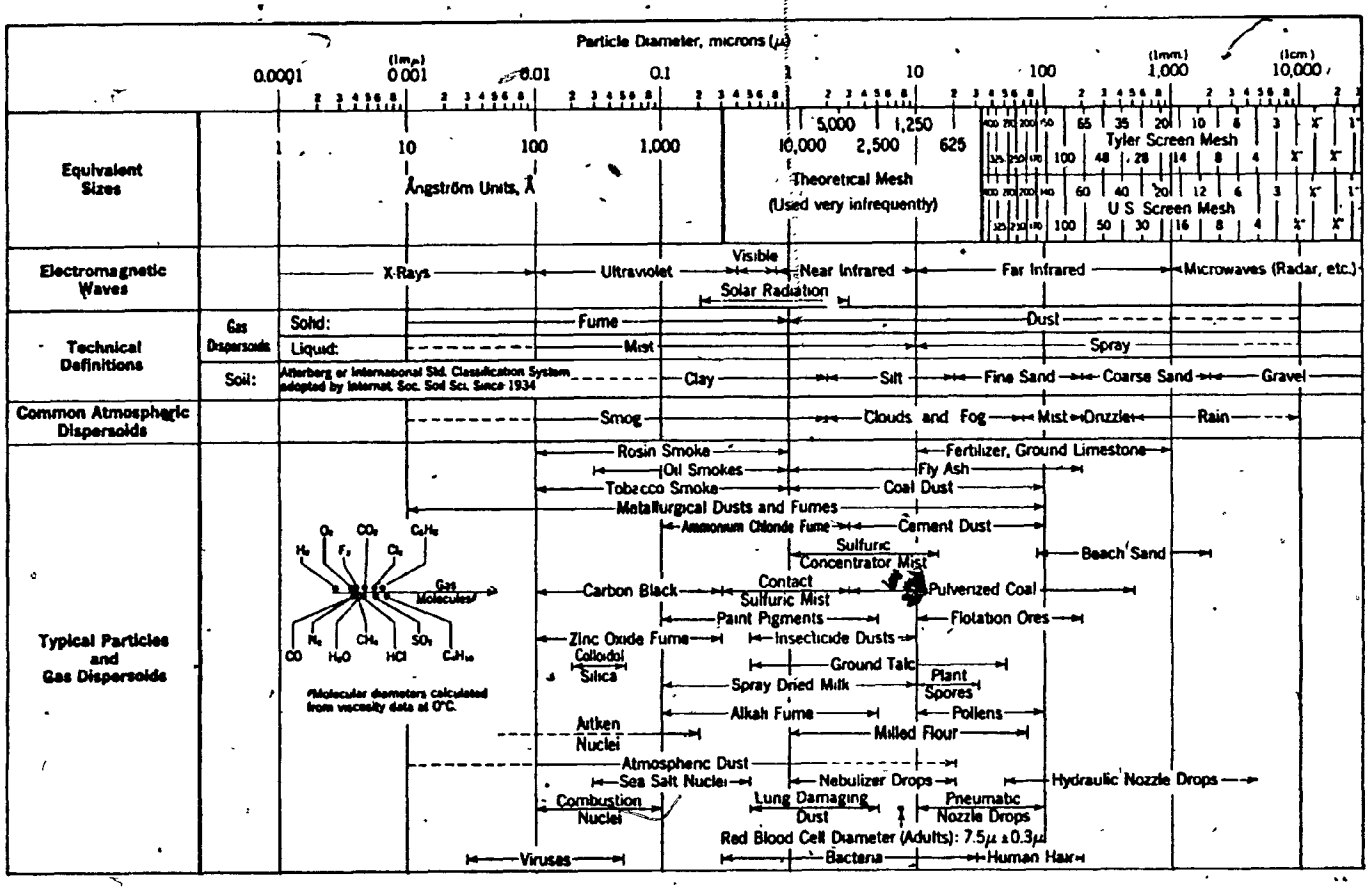


Table 2.1 Particle size for some typical industrial dispersoids [16].

particulates in stack emissions. The fundamental requirement of a particle-sampling system is that it must collect a representative sample.

An analysis of stack samples is normally carried out by cascade impactors [17]. An impactor is a mechanical fractionating device which separates particles by size due to the differences in their aerodynamic properties. Satisfactory size fractionation from approximately 0.5 μ upward has been achieved [1]. Ambient air samples may also be analysed via electrostatic, thermal precipitation, centrifugal, tape sampler, and high volume sampling methods [18]. The two latter techniques are widely employed, and both use filter-paper collectors through which air is drawn for a predetermined time period.

Among the centrifugal methods the Bahco dust classifier [19] has been used extensively. In this instrument dust is fed into an air stream in the annular space between parallel rotating plates and in each stage the dust is divided into two fractions, one deposited on the periphery of the wheel and the other carried forward. By varying the air velocity, a number of different fractions can be detected.

In addition to the general methods mentioned the increased diffusivity of ultrafine particles has been employed to yield an estimate of particle size. This is accomplished by passing the gas sample at low velocities through long narrow channels or bundles of capillary tubes, called a diffusion battery [17]. The smaller particles will be

removed first into the walls of the channels by the mechanism of diffusion.

A number of optical techniques have also been developed. The greater resolving power of electron microscopes extends the range down to approximately 0.05 μ . Photometric methods based on scattering or absorption of light have a lower limit of about 0.3 μ for monodisperse or uniform particle-size distributions. Optical methods based on light scattering are used for continuous monitoring of stack gases in many industries. Radiation interference (visible, optical and beta) has been successful in the analysis of particulate loadings in emission sources where estimates of the particulate concentration can be made using either transmittance or reflective measurements. Both of these measurements are qualitative and are used only for comparative purposes.

Particulate and carrier-gas chemical composition exerts an influence on the electrical properties, toxicity, reactivity, wettability and most other particle properties and thereby, on the choice of control and auxiliary handling equipment. If more specific information is required, a number of clorimetric and spectrometric techniques are available. A particularly sensitive method is the atomic absorption spectroscopy for the determination of most metals in the microgram to monogram range.

2.3 PARTICLE SIZE AND STRUCTURE

Particle shape and surface condition influence handling characteristics, chemical reactivity, absorption potential, and flammability limits. Particle shapes of dispersoids include a myriad of types from simple spheres to complex stars and chainlike aggregates. Fogs, mists, and some smokes are composed of shperical liquid or tarry droplets. Many fly-ash particles, produced in the combustion of pulverized coal, are hollow spheres or cenospheres, frequently with much smaller satellite particles, attached to their surfaces [18]. Dust particles usually are irregular in shape as the result of multiple fractures which occur in crushing or grinding. Metallurgical fumes have a starlike or platelike shape, while others are needlelike and tend to form agglomerated chains. McCrone has published a photomicrographic atlas of dust components that permits recognition of up to 90% to the particles in a typical urban sample [20].

The concept of particle size is useful in the study and classification of dispersoid particles, and their properties when summed over all the particles present in the collection, yield information as to the overall properties of the particle population. Particle size may be uniquely defined only for the special case of shperical particles for which it is completely specified by the particle diameter. For the general case of nonspherical particles, particle size may be defined in terms of equivalent diameters which depend on various geometrical or physical properties. For example, with irregularly shaped dust particles, the

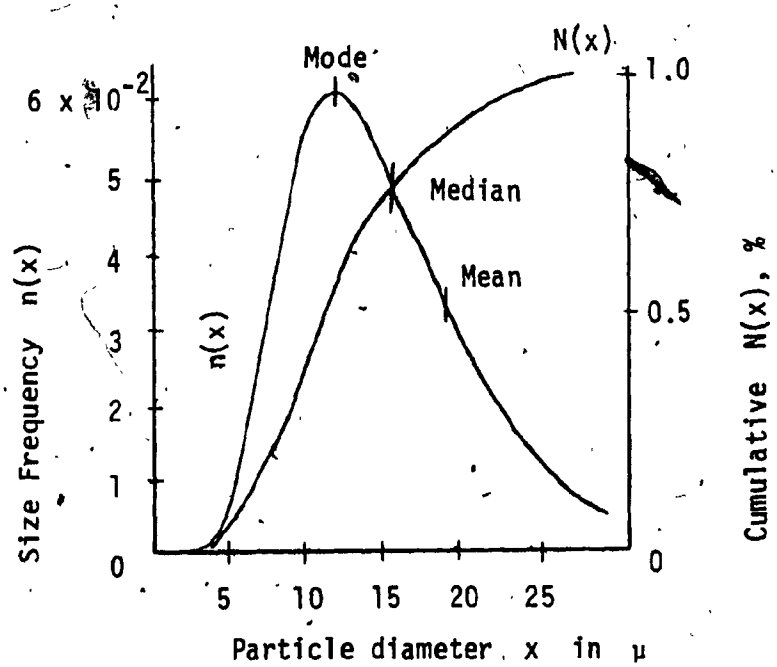
average dimension along three mutually perpendicular axes, or the diameter of the sphere having the same volume or the same surface area as the irregular particle may be chosen as the representative dimension. Another approach is to use some physical property such as the settling rate of the particle in a given fluid to derive an equivalent diameter. A summary of some of the more usual methods for defining equivalent diameter of particles along with practical methods for their determination are given in [21].

It is evident that the size of irregularly shaped particles will depend on the method used in determining the average dimension or equivalent diameter. In general, no two methods will result in the same value. For very irregularly shaped particles these discrepancies may be significant, hence, for particle shapes such as plates, rods, or stars, the concept of equivalent diameter is of very limited usefulness. For these cases, the specific surface or settling rate parameter is more relevant.

Virtually all dispersoids, whether natural or man made, have a range of sizes and shapes. Liquid or tarry dispersoids, such as fogs and tobacco smoke, are spherical by nature but usually vary in diameter over a wide range. Solid particles are almost invariably irregular in shape. Particle-size measurements therefore, must include not only the determination of individual particles but also the size distribution.

2.4 PARTICLE-SIZE DISTRIBUTION

Lee and Goranson [22] have demonstrated that the particle size distribution may be approximated by a long-normal function. Their conclusion was based on 150 particulate samples analysed using cascade impactors. The log-normal density function $n(x)$ and the resulting cumulative distribution $N(x)$ are illustrated in Figure 2.2 [23]. Figure 2.3 depicts the cumulative distrubution function plotted on log-probability coordinates. It will be noted that in this coordinate system, the cumulative probability is a linear function of particle size. For many dispersoids the skewness of the $n(x)$ curve may be eliminated by considering the logarithm the size parameter x as $u = \ln x$. This is shown in Figure 2.4.



$$N(x) = \int_0^x n(x)dx$$

Fig. 2.2 Log-normal and cumulative-distribution curves

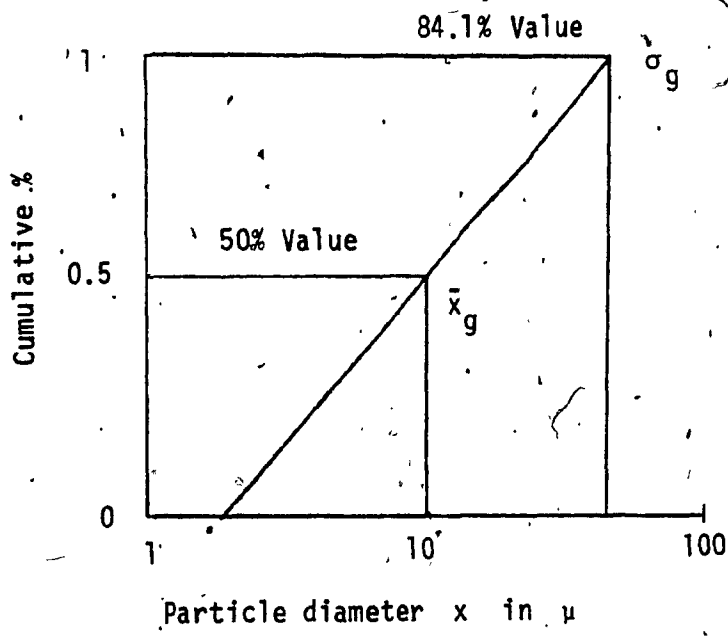


Figure 2.3 Cumulative distribution on log-probability coordinates

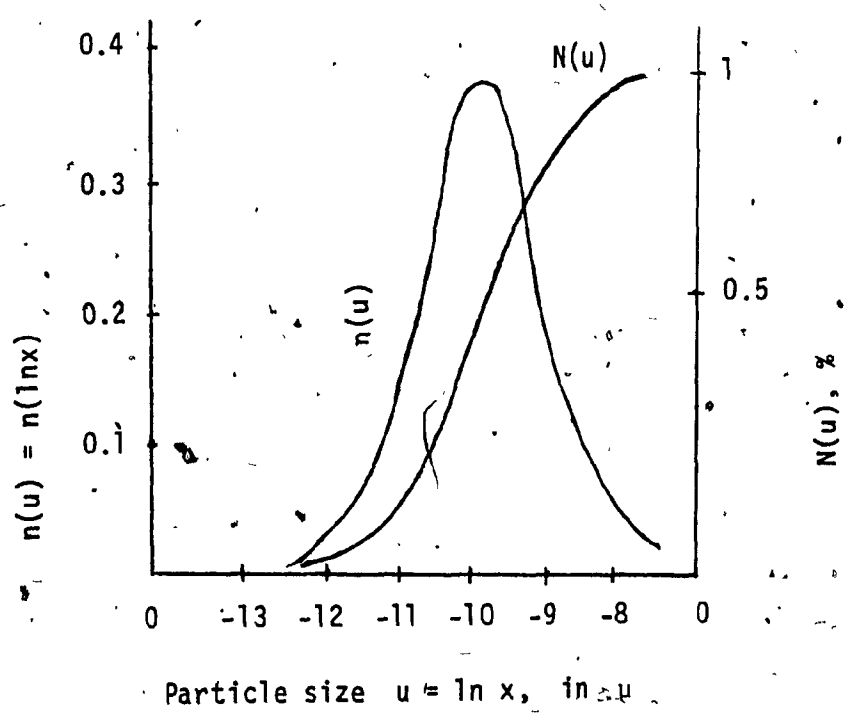


Figure 2.4 Log-normal particle distribution with logarithmic abscissa.

In the log-normal distribution of Figure 2.4, the curve for $n(u)$ is a normal probability curve in u, centered about a mean value $\bar{u}$ and having a standard deviation σ_u. This curve is define mathematically by [21]:

$$n(u) = \frac{1}{\sqrt{2\pi}\ \sigma_u} \exp\left[-\frac{(u-\bar{u})^2}{2\sigma_u^2}\right] \tag{2.1}$$

where u is the logarithm of the particle diameter, $\ln x$

$\bar{u}$ is the logarithm of the mean geometric diameter, $\bar{x}_g$; and

σ_u is the logarithm of geometric standard deviation

The cumulative size distribution function $N(u)$ is obtained by integrating Equation (2.1) using the transformation

$$t = \frac{u-\bar{u}}{2\sigma_u} \tag{2.2}$$

to obtain

$$N(u) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{t} e^{-t^2}\, dt = \mathrm{erf}(t) \tag{2.3}$$

The log-normal distribution has several properties which are worth noting:

a) It is completely specified by the two parameters $\bar{x}_g$, the geometric-mean particle size, and σ_g, the geometric standard deviation.

b) The geometric standard deviation is identical for all methods for specifying particle-size distributions, whether by particle number, surface, mass or any other quantity. Plots of the integral distribution function $N(x)$ on log-probability paper are parallel lines. In view of this, transformations among the various particle-size parameters and statistical diameters are greatly facilitated both analytically and graphically.

c) Values of the mean, median, and mode particle-sizes are easily calculated. For example,

$$\bar{x} = \text{mean diameter} = \bar{x}_g \, e^{(\frac{1}{2}) \ln^2 \sigma_g} \tag{2.4}$$

$$x_{\frac{1}{2}} = \text{median diameter} = \bar{x}_g \tag{2.5}$$

$$x_p = \text{modal diameter} = \bar{x}_g \, e^{-\ln^2 \sigma_g} \tag{2.6}$$

These are illustrated graphically in Figure 2.2.

d) The geometric-mean diameter, $\bar{x}_g$, and the geometric standard deviation, σ_g, may be found by a graphical procedure as illustrated in Figure 2.3 where:

$$\bar{x}_g = 50\% \text{ value of } x \tag{2.7}$$

$$\sigma_g = \frac{84.1\% \text{ value of } x}{50\% \text{ value of } x} \tag{2.8}$$

2.5 COLLECTION EFFICIENCES

Particle size is normally used to illustrate the fundamental relation between particle characteristics and the gas-cleaning method to be utilized. Fly ash from pulverized coal, with a typical particle size of 50% less than 10 μ, may be cleaned inefficiently with small diameter multicyclones and, at high efficiency with electrical precipitators, or with a combination consisting of a cyclone and precipitator cleaner. Bag filters or scrubbers could also be used as far as particle size in concerned, if other factors do not militate against these methods.

The collection efficiency of a control device is a measure of its effectiveness in removing the particulates from a gas stream. The overall efficiency, which is usually stated in per cent is defined in [24]

$$\eta(\%) = \frac{P_p - P_o}{P_p} \times 100 = \frac{P_c}{P_p} \times 100 \tag{2.9}$$

Where,

P_p is the amount of pollutants entering the control device,

P_o is the amount of pollutants escaping the control device, also denoted as the penetration, and

P_c is the amount of pollutants collected by the control device.

Efficiency can also be expressed by the decontamination factor (DF) which is defined as [25]

$$DF = \frac{P_p}{P_o} = \frac{1}{1-\eta} \tag{2.10}$$

Equation (2.10) shows that for an efficiency of 99.999% the decontamination factor DF is 10^5. The logarithm to the base 10 of the decontamination factor is the decontamination index [25]. In this example the index is 5. As indicated earlier the efficiency of collection is affected by the size of the particles. This aspect of particulate control introduces the concept of fractional efficiency, i.e., the efficiency over a given particle-size range with which the particles within that range are collected. For particles at a single diameter x, the efficiency of the control device is defined as:

$$\eta(x) = \frac{P_p(x) - P_o(x)}{P_p(x)} = \frac{P_c(x)}{P_p(x)} \tag{2.11}$$

where $P_p(x)$, $P_o(x)$ and $P_c(x)$ are the amounts of the pollutant, at the diameter x, entered, passed through, and collected, respectively by the control device. Efficiency may also be expressed in terms of particle mass (volume diameter), surface area (surface area diameter) and finally the total number of particles treated. The expressions appropriate to each method may be found in [21].

CHAPTER III

FABRIC FILTRATION

CHAPTER III

FABRIC FILTRATION

3.1 OPERATING PRINCIPLES

One of the oldest and most reliable mechanisms for the removal of dry solid particulate matter from a gas stream, is fabric filtration. Fabric filters operate by trapping the dust on the upstream side of the filter while allowing the gas to pass through the interstices between the woven threads of the fabric. While these interstices may be as large as 100 μ in a typical commercial bag filter, such a collector may trap dust particles as small as 0.5 μ [26]. The capability of the fabric filter to collect fine dust particles, is the direct result of the built up of a porous layer of dust on the dirty-gas side of the cloth. The accumulated filter cake layer, blocks the large interstices, thereby resulting in much smaller passage openings.

The formation of the filter cake layer is controlled by several factors, the most dominant being: agglomeration of upstream fine particles, impaction of larger particles on the fiber, diffusion of submicron particles into the fiber, electrostatic attraction and repulsion, thermal effects, coarce sieving by the cloth and finally, fine sieving by the filter cake layer itself [27]. The particle layer that accumulates on the fabric surface, makes it difficult to predict the filter pressure loss and resulting collection efficiency.

The performance of the bag filter has not been successfully analyzed theoretically, primarily because of the complications introduced by the filtering action of the dust layer. It is standard practice to allow fabric filters to operate until such time as a prescribed reduction in the gas velocity and a concomitant increase in the pressure drop occur. At this point, the filter is cleaned by a dust-dislodging operation and filtration is restored.

Fabric filters are usually made in the form of tubular bags, and the structure in which the bags hang is known as a baghouse. On large units the tubular bags may be as much as 1 ft in diameter and up to 60 ft in length [28]. Baghouses are manufactured to handle airflows ranging form below one hundred CFM for small manually cleaned collectors, to several million CFM for large automatically cleaned units [6]. The baghouse construction has found a wide range of applications in many industries, including mining, food processing, grain elevators, soap detergents, plastics, carbon black, element manufacture, electric arc furnaces, and nonferrous metal smelting processes [29].

A major advantage of the fabric filter is its high efficiency at a variety of gas stream velocities extending to practically zero gas flow. The disadvantages include large size, relatively high pressure loss, high maintenance due to the cost of bag replacement and operational limitations to free stream temperatures below the mixture

dew point. In the presence of ambient moisture, bag filters become clogged and plug-up very rapidly. Further, care must be exercised to assure that the fabric is not exposed to temperatures above those that can be safely tolerated by the materials employed.

3.2 EQUIPMENT CONFIGURATION AND PERFORMANCE CHARACTERISTICS

Baghouses are characterized by their filtering media, the location of the fan with respect to the filter, the methods used to clean the bags as well as the frequency of bag cleaning. Fabric filters are made from a variety of materials such as cotton, wool, Dynel, Dacron, Nylon, Orlon, Nomex, Polypropylene, Teflon, and Fiberglas. Natural fibers (cotton or wool) are typically used for temperatures below $200^{o}F$. Artificial fibers have extended the application of bag filters to temperatures in the 300° to $400^{o}F$ range. Baghouses equipped with lubricated fiberglass can handle corrosive acidic, and alkaline gases up to $600^{o}F$ [30]. A summary of typical fiber materials and their characteristic properties is included in Appendix I.

Depending on the location of the fan in the gas stream, baghouses are categorized as open or pressure type and as closed or suction type. In pressure-type baghouses, the fan is located on the dirty gas side, and the baghouse can be operated with hotter inlet temperatures because of the cooling effect provided by the ambient air. Pressure-type baghouses are generally less expensive since the housing must only

withstand the differential pressure across the baghouse. Maintenance is also reduced since the compartments are accessible and leaking bags can be observed while the compartment is in service. The main disadvantage of the pressure type baghouse is that the fan is exposed to the dirty gases which cause high abrasion and wear rates.

In suction type baghouses, the fan is located after the filtering compartment. In this arrangement, the baghouse is subjected to relative high negative pressures and therefore must be more heavily constructed and reinforced than the pressure baghouses. Since the exhaust gases from each compartment are combined in the outlet manifold to the fan, the location of compartments with leaking bags is difficult to determine and this increases the cost of maintenance. The main advantage of the suction baghouse is that the fan handling the process stream is located on the clean gas side. This reduces wear and abrasion on the fan and permits the use of more efficient fans. Closed suction baghouses are generally used on wet gases (dew points up to 185^{0}F) and in applications involving abrasive dusts [31].

The methods used to clean the bags are generally referred to as: shaker type, reverse air, and pulse jet [32]. The shaker type method of cleaning consists of hanging the bags on an oscillating framework driven by a motor with a timer. The baghouse is separated into several compartments so that at periodic intervals, the gas flow to a compartment is interrupted and the motors connected to the

compartment are activated. The shaker type mechanisms produce a violent action on the bags and, in general, lead to more wear on the bags than other types of cleaning mechanisms. For this reason, shaker type cleaning is used in conjunction with heavier and more durable fabric materials.

The reverse air method of cleaning the bags in accomplished by passing air, countercurrent to the direction of the gas flow in normal filtration, when the compartment is isolated for cleaning. The reverse air is supplied by a separate fan or in some cases, the pressure differential accross the bags can be used to collapse the bags without the aid of a fan. This type of cleaning is used with fragile bags (such as fiberglass) or lightweight bags and usually results in longer life for the bag material. Finally bag cleaning by pulse jet is accomplished via the use of compressed air jets located at the top of the bags. Periodically, a blast of compressed air is introduced causing the bag to expand rapidly and thereby dislodging the particulate. In some cases, this method of cleaning does not require the isolation of the bags to be cleaned from the filtering process so that the extra compartments required for cleaning with the shaker and reverse air type baghouses are not needed. In addition, the pulse jet baghouses can sustain higher filtering velocities through the filter medium (higher air-to-cloth ratios) and consequently the overall size of the baghouse is reduced.

Baghouses are also characterized as to the type of service and frequency of bag cleaning and are generally referred to as either intermittent or continuous duty. Intermittent baghouses are cleaned after filtering is completed, usually at the end of each day, and operate at low dust loadings. Continuous baghouses operate indefinetely and cleaning of a portion of the filter occurs at periodic intervals while the process gases are being filtered by the remaining filter area.

In all baghouses, it is necessary to have some type of pressure-sealing discharge device, because the interior of the collector is under a pressure different from atmospheric. Discharge devices may be manual or automatic. The simplest type of manual discharge device is the slide gate valve, held in place by a frame and sealed with gaskets. When the hopper needs to be emptied, the collector must be shut down, and the plate is pulled out of the frame to discharge the collected material. The simplest form of automatic, continuous-discharge device is the double-tipping valve, available in gravity-operated and motorized versions as shown in Figure 3.1 . Rotary airlocks or star valves are the most commonly used discharge devices on medium and large-size collectors. The general design is that of a paddle wheel which is shaft-mounted and driven by a gear-reduced motor as depicted in Figure 3.2 .

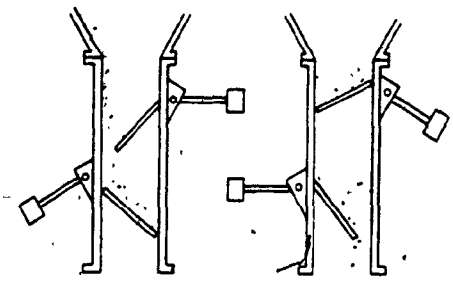


Figure 3.1 Double tripping valve [32].

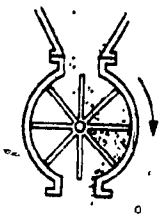
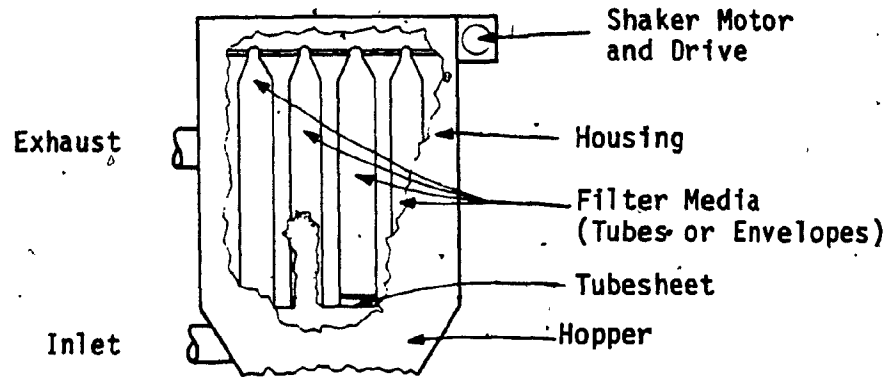
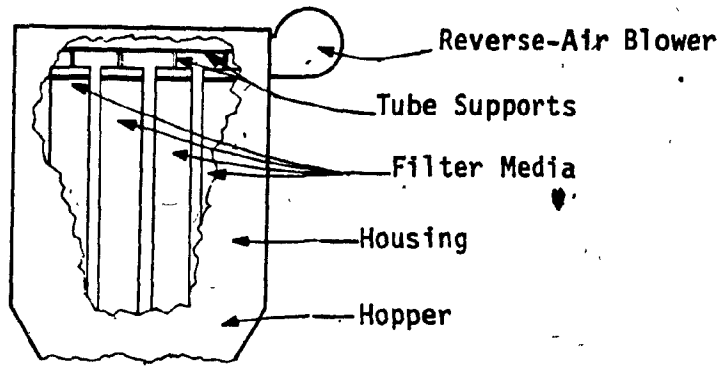


Figure 3.2 Rotary airlock.

The pressure loss across the filtration unit is a function of many variables, such as mechanical design of the baghouse, cloth resistance, filter cake resistance, cleaning technique and efficiency, filtering velocity, dust concentration, temperature, and relative humidity. At present, there are no reliable methods for computing the exact pressure drop through a collector [33]. The "superficial face velocity" of the gas passing through a cloth filter which is equal to the actual volumetric flow in CFM divided by the net cloth area in ft^2 affects the pressure drop and bag life. This ratio is referred to as the air-to-cloth ratio and is the basis for sizing and costing baghouses. High air-to-cloth ratios will reduce the size of the baghouse and the overall costs. The air-to-cloth ratio also determines the type of cleaning mechanism to be used in a given baghouse. Shaker type and reverse air cleaning shown in Figure 3.3 can be used with air-to-cloth ratios of up to 4, while pulse jet cleaning can be utilized with air-to-cloth ratios of up to 15 in some cases. Typical air-to-cloth ratios for the most common dusts, and the three cleaning mechanisms are tabulated in Appendix II. The type of material selected as the cleaning fabric will also dictate the range of air-to-cloth ratios to be used in a particular application. For example, polyester fabrics are normally used with ratios of up to 6, while fiberglass is usually limited to 3 [34]. These limiting ratios are the normal "rule of thumb", and can be exceeded in some cases with light dust loadings.



(a) Shaker-Type Collectors



(b) Reverse-Air Collectors

Figure 3.3 Shaker and reverse air collectors.

CHAPTER IV

WET SCRUBBING

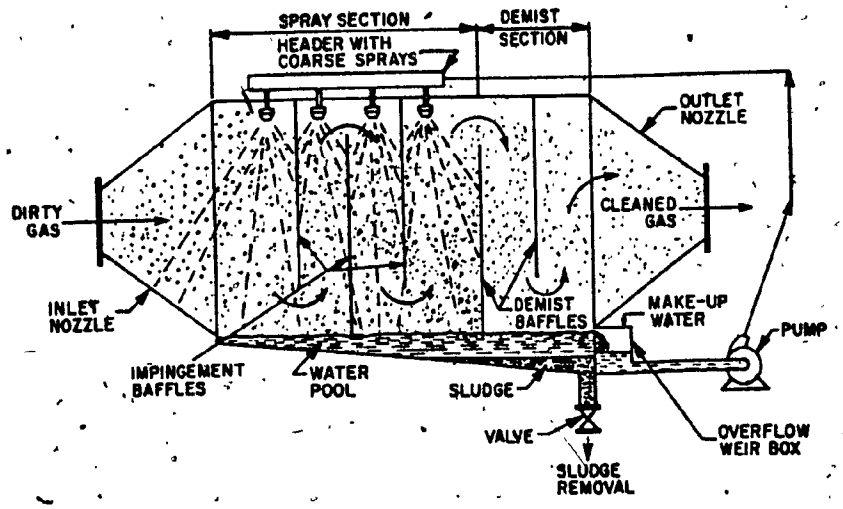
CHAPTER IV

WET SCRUBBING

4.1 OPERATING PRINCIPLES

Wet collectors use water sprays to collect and remove particulate matter. The principal mechanisms involved in wet scrubbing are inertial impaction, interception and Brownian diffusion. The effect of temperature and external forces (gravitational and electrostatic) are not considered important [35]. Collection is also affected by the particle wetting characteristics, condensation of moisture, and drop evaporation. Condensation of vaporization can affect particle size and can force particles toward or away from the drop surface because of vapor flow [36].

Scrubbers used in air pollution control are available in a wide range of types and sizes and they are generally classified as low or high energy scrubbers. Low energy scrubbers of 1 to 6 inches of water of pressure drop, include simple spray towers, packed towers, and impingement plate towers shown in Figure 4.1 . Water requirements may run 3 to 6 gal/1000 ft^3 of gas, and collection efficiencies can exceed 90 to 95% when the particles are above 5-10 μ in diameter [37]. The low-energy scrubber has found frequent application in incinerators, fertilizer manufacturing, lime kilns, and iron foundries. The high energy scrubber, or Venturi shown in Figure 4.2, imparts high velocity to the gas stream by means of a converging-diverging duct



Wetted impingement baffle scrubber.

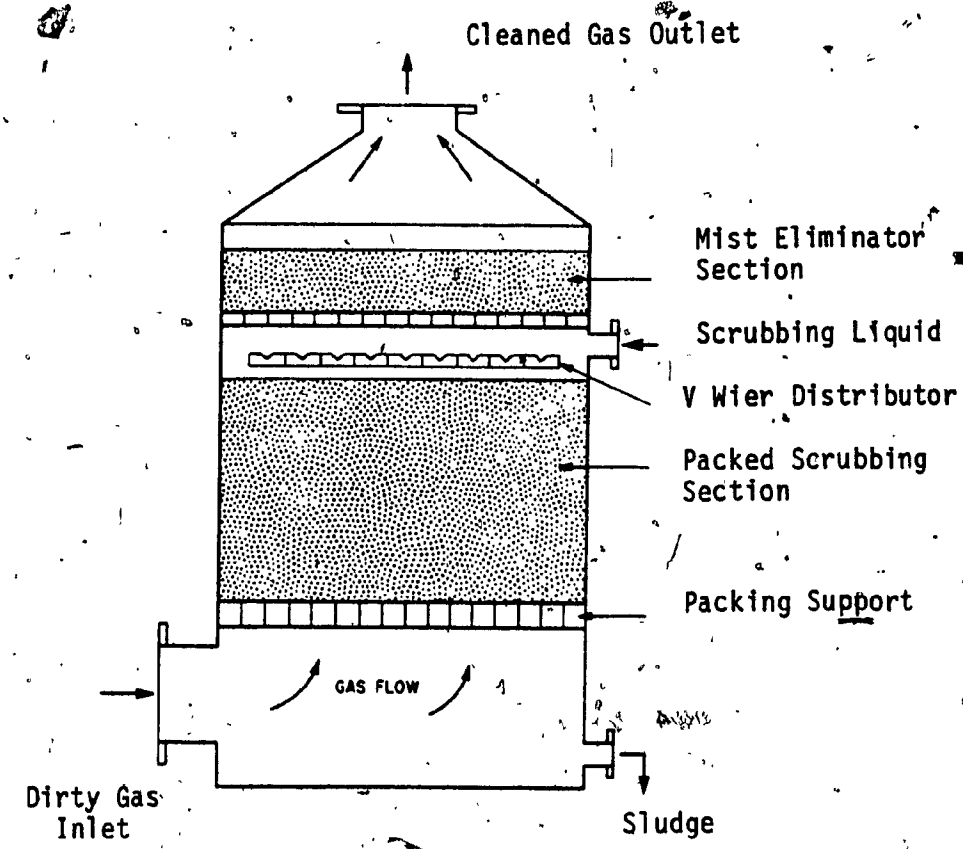


Figure 4.1 Types of low energy scrubbers.

section; and contacts the stream with injected water. The high velocities provide increased collection efficiency, up to 99.5%, but the pressure drop may range from 10 to 60 inches of water. This requires turbocompressor-type fans with high power input. The Venturi scrubber is often used in conjunction with steel furnaces, pulp mills and foundry cupolas [38].

There are a number of applications where venturi scrubbers are the only technically feasible solution to an air pollution problem. If submicron particulate matter is sticky, flammable, or highly corrosive, electrostatic precipitators and fabric filters cannot be used and venturi scrubbers become the only alternative. Venturi scrubbers are ultrahigh-efficiency collectors, which can simultaneously remove gaseous and particulate matter from a gas stream.

Stainless steel, ceramic lined carbon steel or high nickel alloys are the construction material for scrubber equipment [39]. In many control problems where the air stream and its gaseous contaminants are highly corrosive and/or the scrubbing solution is corrosive, scrubber components must be fabricated from corrosion resistant materials. In recent years there has been an increased acceptance of fiber-reinforced plastics. Combination of polyester or epoxy thermosetting resins and glass fiber reinforcements that produce a finished laminate with excellent corrosion resistance and a high strength-to-weight ratio [40] have been used extensively in this

field.

Some disadvantages of the wet scrubber include the disposal of the collected wet sludge, the high energy costs, the high material cost related to services where there is chemical corrosion, the potential problem of plugged nozzles, unavailability of scrubbing liquid of sufficient clarity, and the treatment of corrosive scrubbing liquids. A further disadvantage of the wet scrubber is the very visible white plum which is an inherent characteristic of all wet-scrubber stacks, discharging to atmosphere without downstream gas conditioning.

4.2 PERFORMANCE CHARACTERISTICS OF VENTURI SCRUBBERS

Venturi scrubbers are distinguished from other wet scrubbers by two physical features. First, and most important, is a gas-liquid contacting throat with a constant cross-sectional area over a finite length. In general, the longer the throat, the higher the collection efficiency at a given pressure drop, provided the throat is not so long that frictional losses become significant. For a cylindrical throat, a 3:1 ratio of throat length to diameter is the minimum required to achieve optimum use of fan horsepower [41]. The second feature is the energy recovery section (expander) at the throat discharge which recovers kinetic energy from the mixture of gas and scrubbing liquid drops.

Venturi scrubbers are used in applications where pressure drops of between 10 and 100 inches of water are necessary. Below 10 inches of water, low-energy impaction scrubbers are preferred, because the velocities are so low that turbulent losses are not encountered and the expander section is unnecessary. Pressure drop for gas flow through venturi scrubbers is caused by friction with stationary surfaces and by the acceleration of liquid. If the liquid is introduced at a velocity U_L in the direction of gas flow and finally attains the gas velocity U_G the pressure drop is given by [42]

$$\Delta P = 1.0 \times 10^{-3} (U_G - U_L)^2 (Q_L/Q_G) \tag{4.1}$$

where ΔP is pressure drop (cm of water), U_G is the gas velocity relative to duct (cm/sec), U_L is the liquid velocity, relative to duct (cm/sec), Q_L is the gas volumetric flow rate (m^3/sec), and Q_G is liquid volume flow (m^3/sec).

Venturi scrubbers operate at throat velocities varying between about 150 and 500 fps, and at liquid-to-gas ratios varying between 3 and 20 gallons per thousand cubic feet scrubbed, with 7 to 10 gal/Macf being the most common range for efficient operation [43]. For a given particle size, higher removal efficiency requires greater pressure drop or greater energy input to the scrubber. Figure 4.3 shows typical collection efficiency curves at five

different pressure drops, in a well-designed venturi scrubber.

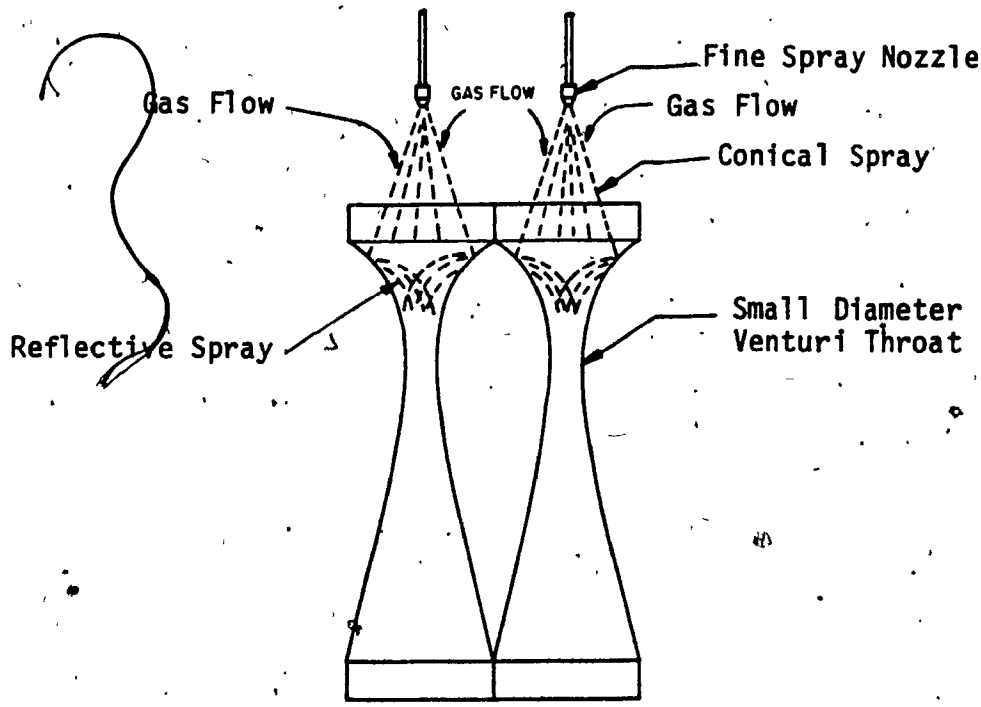


Figure 4.2 Multiple venturi scrubber.

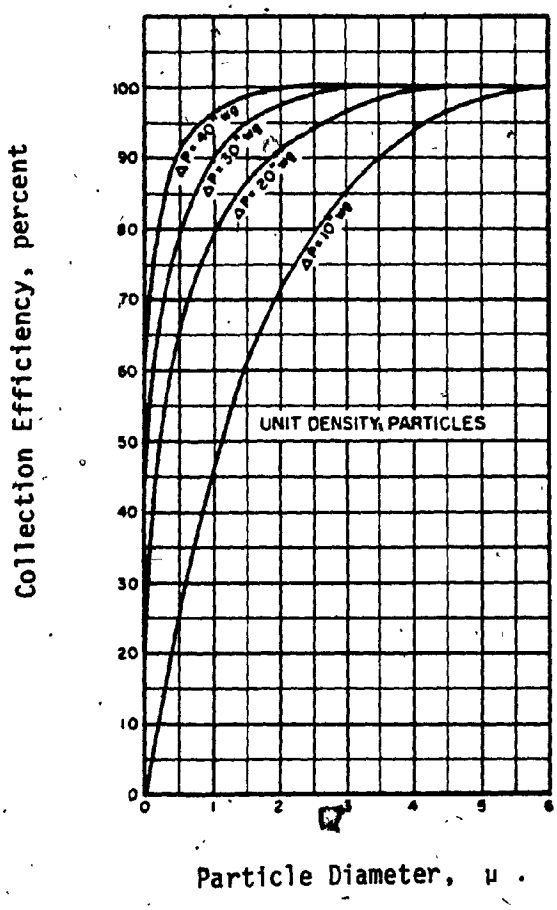


Figure 4.3 Typical venturi scrubber collection efficiencies [44].

CHAPTER V

ELECTROSTATIC PRECIPITATION

CHAPTER V

ELECTROSTATIC PRECIPITATION

5.1 FUNDAMENTALS

Electrostatic precipitators are particulate extraction devices which utilize electrostatic forces to separate the polluting particles from the process gas stream. The principles of electrostatic attraction and repulsion were known as early as 600 BC. The first analytical investigation into the nature of this phenomenon was conducted by Coulomb in the later part of the 18th centuary and this has formed the basis of current electrostatic precipitator theory. Practical applications of this technique did not materialize until the development of high voltage power equipment in the early part of the twentieth century.

At present, electrostatic precipitators account for the largest gas volume cleaned and mass of particles collected. Their popularity is attributed to the extreme versatility of the equipment which is capable of delivering virtually complete collection of large as well as minute solid or liquid particles. Further, electrostatic precipitators can be operated at high temperatures and pressures, require little power and introduce relatively small pressure drop. Such precipitators have been employed in a great variety of gas-cleaning problems with collection efficiencies as high as 99.9 per cent, capacities, of up

to 4,000,000 cfm, and at gas temperatures over 1,000°F [45]. It should be noted, that in 1970, there were over 5,000 installations in the United States cleaning 700 million CFM of exhaust gases originating at thermal power stations, incinerators, and industry. This represents an investment in clean air of over $1 billion [46].

However, the electrostatic precipitator has some serious drawbacks. There are certain dusts which can be collected by a precipitator only with great difficulty and it cannot handle gaseous pollutants. In fact, its use with particulates may require that certain gaseous pollutants be present in order to achieve good collection efficiency. For instance, a power plant precipitator will not satisfactorily collect fly ash from low-temperature flue gases unless a certain amount of sulfur trioxide is present. This difficulty can be overcome by operating the precipitator on flue gases at elevated temperatures.

5.2 OPERATING PRINCIPLES

Basically, the electrostatic precipitation process can be separated into the following stages: a) A method of providing an electrical charge on particles, b) a means of establishing an electric field, which must be experienced by the particles to remove them from the gas stream to a collecting electrode, and c) a mechanism for removing the particle layers from the electrode surfaces for discharge to an outside receptacle. In practice the electrostatic

precipitator is commonly found in one of two basic forms. In its simplest configuration, the precipitator comprises a grounded cylinder, designated as the collecting or passive electrode and concentric with it, a high-potential wire called the corona discharge or active electrode. This arrangement is depicted in Figure 5.1. The alternative design, shown in Figure 5.2 consists of two grounded parallel plates (the collecting electrodes) together with an array of parallel discharge wires precisely aligned in a plane midway between the plates. The discharge electrodes are maintained usually at a negative voltage of 40,000 V or higher [47]. The resulting magnitude of the collecting electric field is between 4 and 5 kV/cm, and the electric force acting on a charged 1 μ particle, is about 3,000 times that of gravity [48].

Once a sufficient difference of potential is developed between the discharge and collecting electrodes, a corona discharge is created about the active wire pole. The corona serves as a copious source of unipolar ions of the same polarity as that of the discharge electrode. The ions, in migrating across the interelectrode space under the action of the impressed electric field, attach themselves to the particulates moving with the gas through the system. The resulting charged particles are attracted to the collecting surface and hence are extracted from the gas stream.

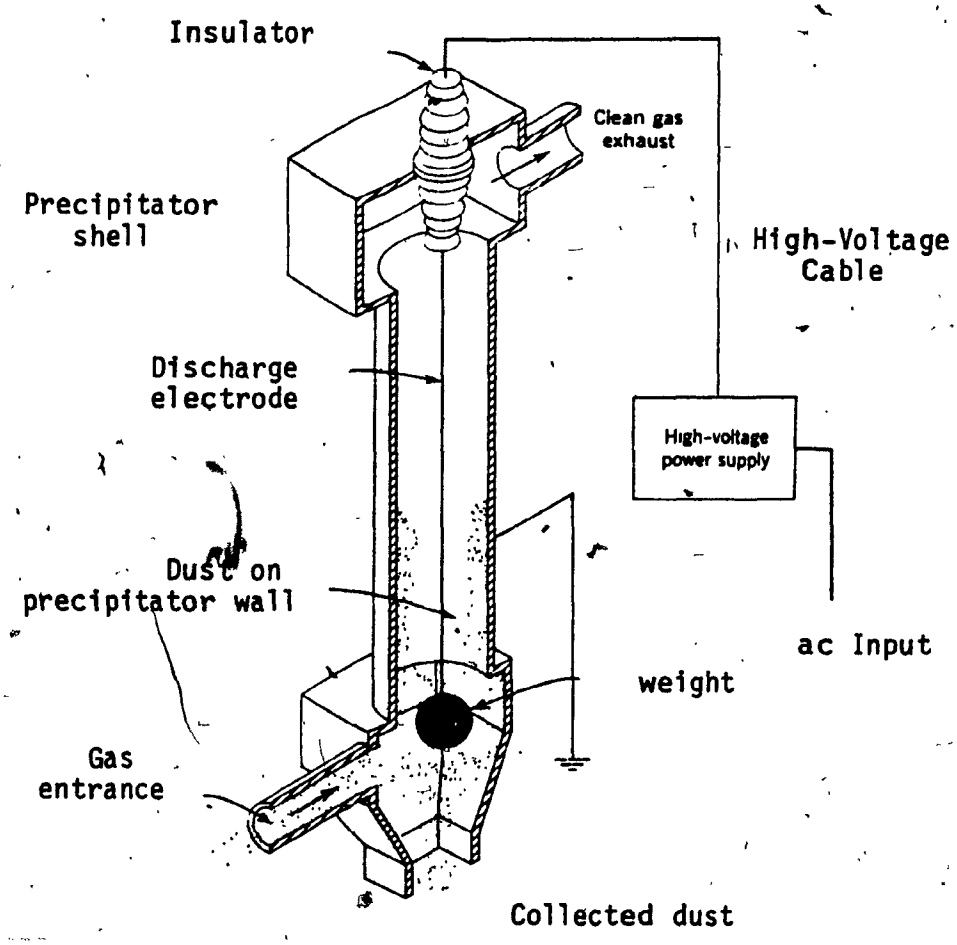


Figure 5.1 Schematic of a wire and pipe precipitator.

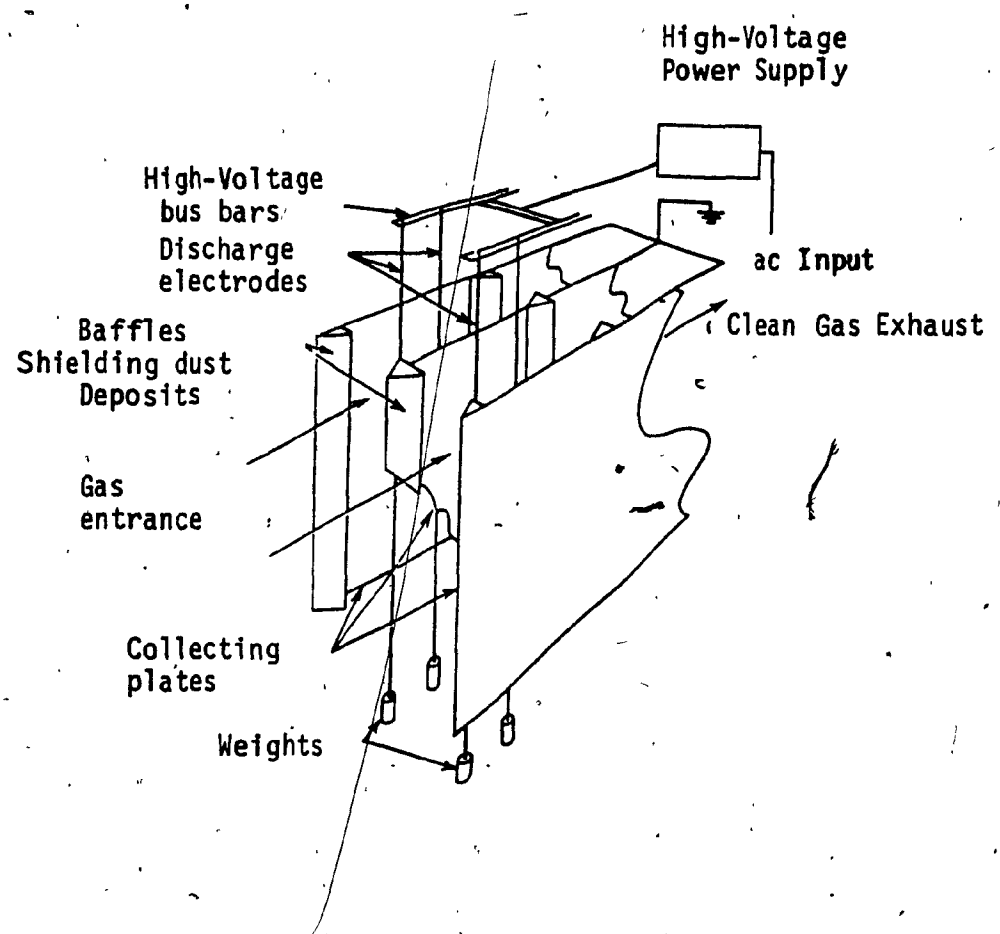


Figure 5.2 Schematic of parallel-plate precipitator

Solid particles build up a layer on the collecting surface. To assure continued efficient operation, the accumulated deposit is dislodged periodically by rapping or flashing and allowed to fall into a hopper for subsequent removal. Liquid particles (droplets) do not require external intervention since they tend to form a film in the collecting surface, which subsequently drips off under gravity into a collecting sump. Various modifications of the basic

precipitator designs are possible. For example, the two stage model employed chiefly in domestic and commercial air purification applications, in conjunction with air conditioning systems, divides the particle-charging and precipitating functions into two adjacent segments. However single-stage models represent by far the majority of industrial applications installed to decontaminate exhaust gas streams.

The details of the corona discharge, electric field, and associated collection efficiencies will be described in greater detail in the following sections.

5.3 CORONA DISCHARGE AND PARTICLE CHARGING

5.3.1 Generation of the Corona

The generation of the corona is a phenomenon which occurs when electrical current flows in a gas. Although electrical precipitation is physically possible using other means such as radio-activity [49], and ultra-violet radiation of X-rays to produce charged particles, no other method has proved technically feasible or economically competitive with the corona.

Peek [50] and Loeb [51], have demonstrated that if the potential difference between two electrodes is raised sufficiently, the gas near the more sharply curved electrode breaks down at a voltage less than the spark-breakdown value for the gap length in question.

This incomplete breakdown is called corona and appears in the air as a highly active region of glow, which takes on a variety of shapes extending into the gas a short distance beyond the discharge electrode surface. The initiation of the corona discharge requires the availability of free electrons in the gas in the region of the intense electric field surrounding the discharge electrode. Since the supply of these electrons depends on the random action of ionizing sources such as natural radioactivity and cosmic rays, the corona discharge is intermittent at voltages very near the corona threshold.

In the case of a negative discharge wire, free electrons in the high-field zone near the wire are accelerated to high velocities and energy levels. These electrons, upon impact with gas molecules cause orbital electrons to be released. These released electrons are also accelerated and continue the ionization, giving rise to the cumulative process termed an electron avalanche. The positive ions formed in this process, are accelerated toward the wire. By bombarding the negative wire and giving up relatively high levels of energy in the process, the positive ions cause the injection from the wire surface of secondary electrons which help to maintain the discharge.

Electrons are attracted toward the anode and as they move into the weaker electric field away from the wire, they tend to form negative ions by attachment to the neutral oxygen molecules. These ions form a dense unipolar cloud occupying most of the interelectrode

space and constitute the only current in the entire space outside the region of corona glow. The effect of this space charge is to retard the further emission of negative charge from the corona and in so doing, limit the ionizing field near the wire and stabilize the discharge. When the corona starting voltage is reached, the current increases slowly at first and then more rapidly with increasing voltage. Further increase of the voltage causes complete breakdown of the dielectric gas. This condition is referred to as sparkover and the voltage at which it occurs as the spark-breakdown value. As sparkover is aproached, relatively small increments of voltage give sizable increases in current [52]. This behavior is illustrated in Figure 5.3.

In most industrial applications, negative corona is used because it yields a higher current than the positive corona at the same voltage. In addition the sparkover voltage, which sets the upper limit to the operating potential of the precipitator is usually greater for a negative corona [53]. The only exception to the use of negative corona occurs in domestic air-cleaning application, since negative corona often produces physiologically objectionable ozone in greater quantities [54].

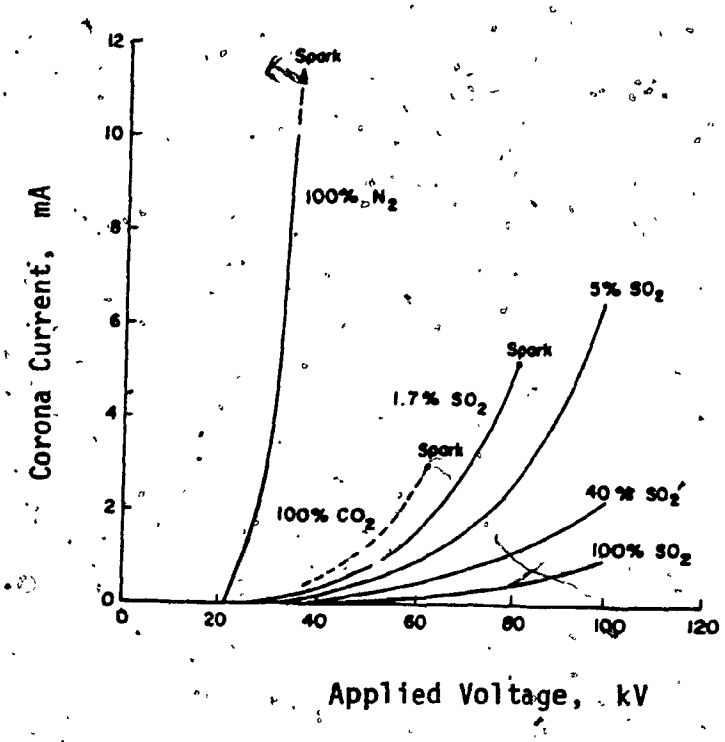


Figure 5.3 Negative corona curves for nitrogen-sulfur dioxide mixtures (6-in. tube, 0.109-in. wire) [52].

5.3.2 Current Voltage Characteristics

The Current-voltage characteristics for the corona are functions of many variables the most important of which are gas composition, temperature and pressure, electrode geometry, the thickness and properties of the collected dust layer, and lastly

the concentration and particle size of the suspended dust. For maximum precipitation, the optimum current-voltage relationship must create conditions which tend to minimize the current and power required to begin the corona ionization process and maximize the average voltage gradient across the discharge and collection electrodes while limiting the amount of sparkover to an acceptable rate.

The simplest precipitator geometry for purposes of analysis is the concentric wire-cylinder configuration. Very approximate calculations also are possible for symmetric parallel plate or duct electrode systems. Experimental measurements of corona current-voltage relations for concentric cylinder and parallel electrodes, were made by Cooperman [55, 56]. Comparisons of experimental results with available analytical predictions are shown in Figure 5.4.

The corona current for a given precipitator and gas is determined almost entirely by the electric field near the active wire electrode. In the wire-cylinder electrode configuration, the electric field at any point for the condition of no current flow is given by [57].

$$E(r) = \frac{V}{r \ \ln (b/a)} \tag{5.1}$$

where $E(r)$ is the electric field at radius r, Volts/meter,

V is the potential, Volts

r is the radius, meters,

a is the radius of corona wire, meters, and

b is the electrode spacing, meters

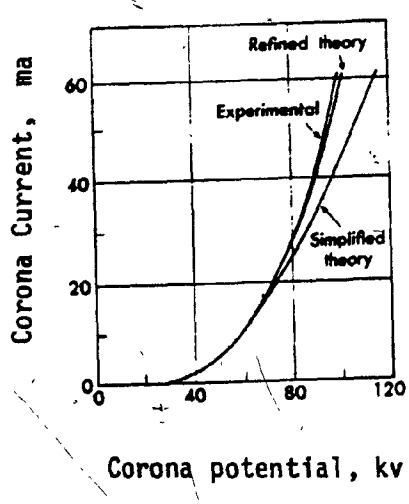


Figure 5.4 Theoretical and experimental V-A corona characteristics.

Increasing the wire-cylinder potential, the field near the wire increases until a corona is initiated. Peek [50] has developed the following empirical relationship for corona initiation in air

$$V_c = 3 \times 10^{-4} \; a \; m \; d \; (1 + 0.3\sqrt{d/a}) \; \ln (b/a) \qquad (5.2)$$

where V_c is the voltage required for corona initiation, Volts,

m is the wire roughness factor, dimensionless,

b is the electrode spacing, meters,

a is the radius of corona wire, meters, and

d is the relative air density, defined as $(\frac{To}{T}) \cdot (\frac{P}{Po})$ where To is $298^{o}K$ and Po is 1.0 atm.

As shown by Eq. (5.2) the smaller the discharge-wire diameter the lower the voltage required to initiate corona. When the voltage is increased beyond the value required for the corona initiation, there is a corresponding increase in current.

5.3.3 Particle Charging

When gases incorporating suspended particulate mater are passed through an electrostatic precipitator, the great bulk of the particles acquire an electric charge of the same polarity as that of the discharge electrodes. Two distinct particle charging mechanisms are generally considered to be active in electrostatic precipitation. The most dominant charging mechanism is bombardment of the particles by ions moving under the influence of the applied electric field. A secondary charging process occurs as a result of the attachment of ionic charges to the particles via ion diffusion. The latter depends on the thermal energy of the ions and not on the electric field. In practice, the field-charging process predominates for particles larger than about 0.5 μ diameter, whereas, the diffusion process is most

effective for particles smaller than about 0.2 μ. Both are equally applicable to particles in the intermediate size range between about 0.2 μ and 0.5 μ [58]. The majority of industrial dusts contain particles in the range where both diffusion and field charging are significant. This is especially true of high efficiency precipitators where the smallest particles must be collected.

Among several investigators Liu and Yeh [59] give a method of calculating the magnitude of the charge due to both diffusion and field charging and the result of their approximation is given by:

$$\frac{dq}{dt} = \frac{N_o\, e\, \mu q_s}{4\epsilon_o}\left(1 - \frac{q}{q_s}\right)^2 + \frac{CN_o\, a^2\, e}{2}\left(1 + \frac{q}{q_s}\right) \qquad (5.3)$$

where q is the particle charge, (C),

q_s is the saturation particle charge, (C),

No is the free ion density, (number/m^3),

e is the electronic charge, (C)

μ is the mobility of ion, (m^2/V-second),

E_o is the permittivity of free space, (C^2/J-m),

C is the effective velocity of ion cluster, (m/second),

a is the particle radius.

The first term in Eq. (5.3) gives the effect of field charging and the second term is a correction factor which approximates the additional charge imparted by the diffusion process. The calculations agree

reasonably well with experimental data obtained by Hewitt [60]. Figure 5.5 shows a comparison of particle charge as a function of the ion density-time product computed by Liu and Yeh and the experimental data obtained by Hewitt.

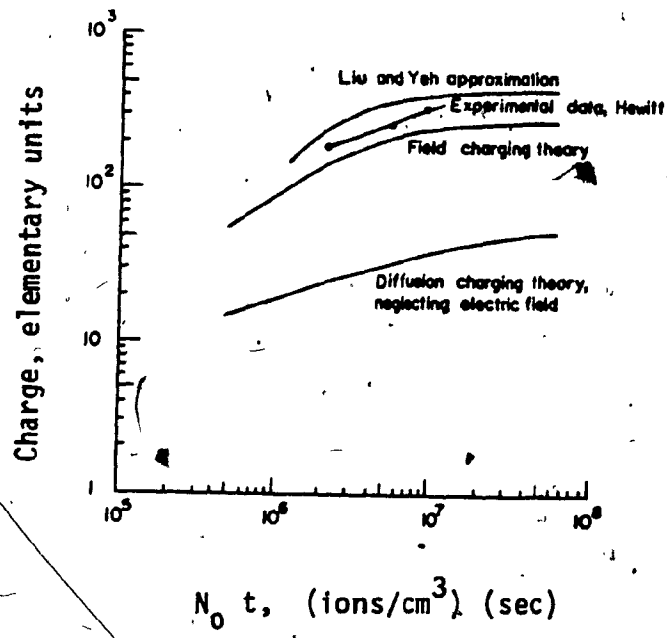


Figure 5.5 Comparison of theoretical and experimental data for 0.4 μ radius particle at Eo = 900 V/cm and 1 atm pressure [59].

5.4 PARTICLE COLLECTION AND EFFICIENCY

Particle collection in an electrostatic precipitator is accomplished when charged particles in suspension move close enough to the surface of the collecting electrode to be trapped by the electric field. Particle trajectories are determined by the combined effects of gas flow and the induced electric field. The electric wind effects of the corona are superimposed. Under turbulent flow conditions, collection efficiency is an exponential function of the collecting area, gas volume, electrical charge, electric field, and gas viscocity. Deutsch [61] derived an analytical efficiency relationship under the assumptions that the partfcle concentration is uniform through the cross section, then the particles are fully charged immediately on entering the precipitator, and that there is no loss or re-entrainment of the collected particles. The resulting equation is:

$$\eta = 1-\exp\left[-(A/V)\omega\right] \tag{5.4}$$

where A is the total collecting surface area, (m^2),

V is the gas volume flow rate, (m^3/sec), and

ω is the particle migration velosity, (m/sec).

The particle velocity can be calculated from the following equation [48]:

$$\omega = \frac{q E_o}{6\pi\theta a} \left(1 + \alpha \frac{\lambda}{a}\right) \tag{5.5}$$

where q is the particle charge, (C),

E_o is the precipitating electric field, $(\frac{V}{m})$,

θ is the gas viscocity, (Kg/m, second),

λ is the mean free-path of the gas molecules, (m),

a is the particle radius, (m),

α is a dimensionless parameter, about 0.86 for atmospheric air.

Equation (5.5), is valid for spherical particles of radii between 0.05 μ and 30 μ in air. The mean free-path of gas molecules, λ, for air at a pressure of 1 atm, has typical values of 0.069 μ at 70°F, 0.106 at 300°F, and 0.128 at 600°F. The mean free-path varies inversely with the gas pressure, so that at one-half normal pressure, the values of λ would be doubled.

Equation (5.4), commonly referred to as the Deutsch equation, is widely used in precipitator design and analysis. A number of researchers, however, have indicated that the Deutsch equation cannot always be used directly to explain precipitator efficiency. Penney [62] states that the Deutsch equation is based on assumptions which probably never occur with industrial dusts and therefore, design work must be based upon test results. Selzer and Watson [63] give the following empirical efficiency equation, derived from data on

37 precipitators installed to eliminate ash from power plants utilizing coal.

$$\eta = 1\text{-exp}\ [-155.71 \times (A/V)^{1.4} \times (P/V)^{.6} \times (S/H)] \qquad (5.6)$$

where A is the collecting plate area, (m^2),

V is the gas colume flow rate, (m^3/sec),

S/H is the sulfur-to-ash ratio, by weight, of the coal combusted, and

P is the power input to the discharge electrodes, (W).

5.5 REMOVAL OF COLLECTED PARTICLES

Removal of the accumulated deposits of particles from the collection electrodes is an essential feature of efficient electrostatic precipitation. Particles can be removed from the collection electrode by draining in the case of liquid aerosol, by flushing the plates with a liquid, or by periodically rapping or vibrating the plates in the case of solid particles. The majority of precipitators in use are of the dry type and dust is removed by rapping [63]. Rapping is necessary not only to remove the collected material from the precipitator but also to maintain optimum electrical conditions in the precipitation zones. A rapping system must be highly reliable, adjustable in intensity and frequency, and capable of maintaining uniform conditions over long periods of time. Another requirement for successful rapping is that it accomplish removal of the dust without excessive reentrainment.

This may be achieved by (a) adjusting the rapping intensity to prevent powdering or excessive breaking up of the dust layer, (b) adjusting the rapping frequency to give optimum dust layer thickness for the most effective removal, (c) maintaining proper airflow and baffling, and (d) rapping only a small portion of the precipitator at a time. Sproull [64] reports that optimum rapping conditions occur if the dust layer slides vertically down the collection plate a distance of perhaps several feet following each rap. Under these conditions, the dust would proceed down the collection plate in discrete steps until it finally falls into the hopper.

Substantial differences exist between U.S. and European rapping methods and approaches [58]. Most European designs are mechanical rappers consisting of hammers mounted on a rotating shaft in such a way that the hammers drop by gravity and strike anvils attached to the collecting plates, as depicted in Figure 5.6. Rapping intensity is governed by the weight of the hammers and length of the hammer mounting arm and cannot be adjusted during operation. The frequency of rapping can be changed, by altering the speed of the rotating shafts. The U.S. designs utilize either pneumatically or electromagnetically operated rappers of the impact or vibration type. Both the intensity and frequency are easily adjusted through electrical control systems.

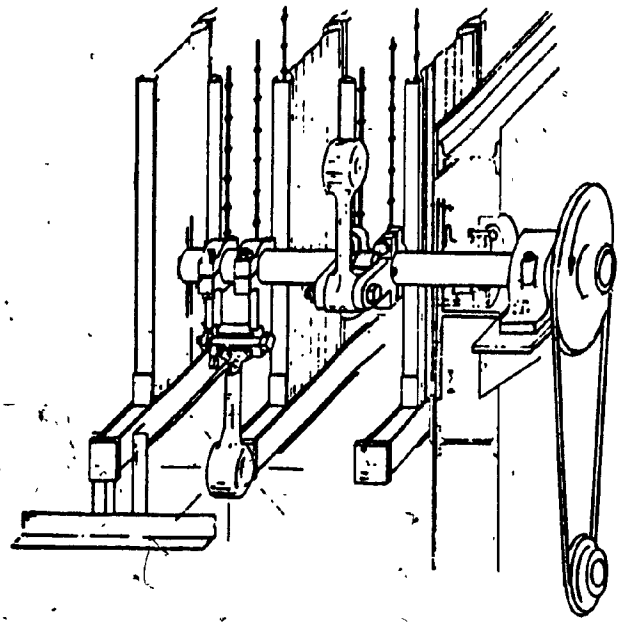


Figure 5.6 Mechanical-type rapper [58].

5.6 PARTICLE RESISTIVITY

The resistivity of the particulate to be collected is extremely important since it directly affects the basic operation of the precipitator. The configuration of the precipitator is such that the corona current from the discharge electrodes must pass through collected dust layers on the plates to reach grounded plate surfaces. If the electrical resistivity of the dust is high, the current flow can result in large voltage drops across the dust layer in accordance with Ohm's law. When resistivity exceeds about 10^{10} ohm-cm it becomes very difficult to achieve reasonable efficiencies with precipitators of

conventional design [65]. Special types of precipitators must then be used, or measures must be taken to reduce resistivity.

The electrical resistivity of the dusts encountered in industrial gas cleaning applications differs widely. Some materials, such as carbon black, have very low resistivity, so that on contact with a grounded metal surface, the particles lose their charge and are easily reentrained into the gas stream. At the opposite extreme, dusts of insulating materials, such as alumina, can have a sufficiently high resistivity that the charge leaks off very slowly. In such cases, the electrical force holding the dust to the collection plate can be very high and the voltage drop across the dust layer can cause breakdown of the interstitial gases within the dust layer.

White [66], Bickelphaupt [67] and McLean [68] have studied the mechanism of current conduction in a dust layer. Two conduction mechanisms are possible in industrial dusts, depending upon their chemical composition, the ambient flue gas temperature, and the water vapor or other substances present in the flue gas. At elevated temperatures (above 600°F), conduction takes place primarily through the interior of the particles, usually referred to as volume conduction, and the resistivity is usually below the critical value as shown in Figure 5.7.

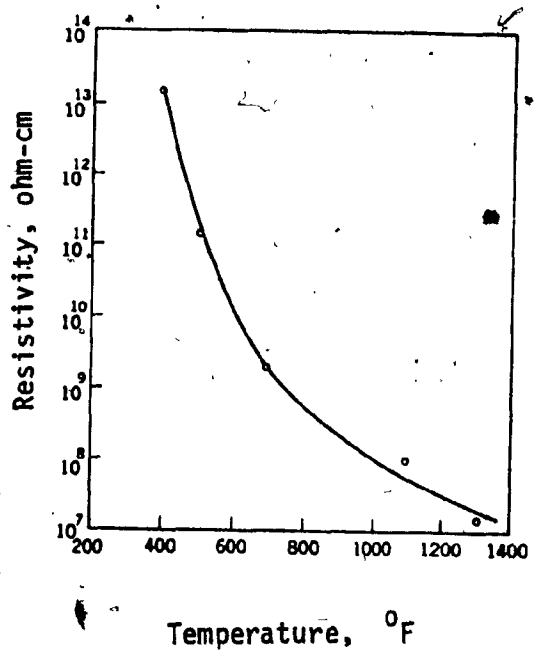


Figure 5.7 Fly ash resistivity at high temperature [66].

At lower temperatures (below 300°F) because of the increased absorption of moisture and chemical films which occur at these temperatures, conduction along the surface of the dust particles becomes the predominant mechanism. In the region of 300°F to 600°F volume and surface conduction are significant. The effect of moisture on resistivity of typical fly ash at 300°F is shown Figure 5.8.

The electrical resistivity of the dust can be altered by a change in the operating temperature or by the addition of other conditioning agents. Conditioning by steam injection, water sprays, or wetting the

raw materials used in the industrial process is a standard method, especially where the natural moisture content of the gases is low [69]. Chemical agents, such as SO_3, NH_3, and NaCl, have found considerable use as conditioning agents but have definite limitations due to cost and application factors [70]. By far the most widely used conditioning agent is SO_3 (or H_2SO_4). This has been used in smelters for a long time [71], and more recently in coal-fired power plants to condition fly ash from low sulfur coals. In most cases the injection of 15 to 20 ppm of SO_3 is sufficient to reduce resistivity by a factor of 100, with corresponding improvements in precipitator electrical operation and collection efficiency [72]. Figure 5.9 shows the great effectiveness of H_2SO_4 vapor in conditioning fly ash in a laboratory test. The positive effect of NH_3 to improve the collection efficiency of fly ash precipitators has also been confirmed [73].

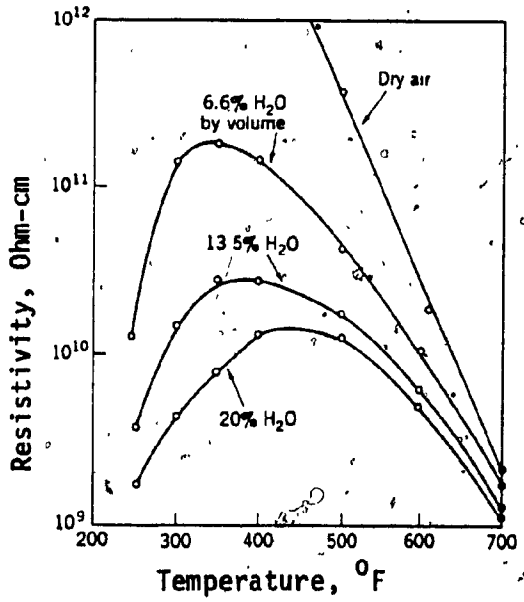


Figure 5.8 Effect of moisture on resistivity [68].

Quantitative determination of particle resistivity usually requires a special high-voltage conductivity cell. Several types of cells have been developed, but all are based on the concept of measuring the leakage current through a particle layer to which a high voltage field is applied. Figure 5.10 shows a high-voltage resistivity cell of the parallel-disk type recommended as a standard by the American Society of Mechanical Engineers (ASME) [74].

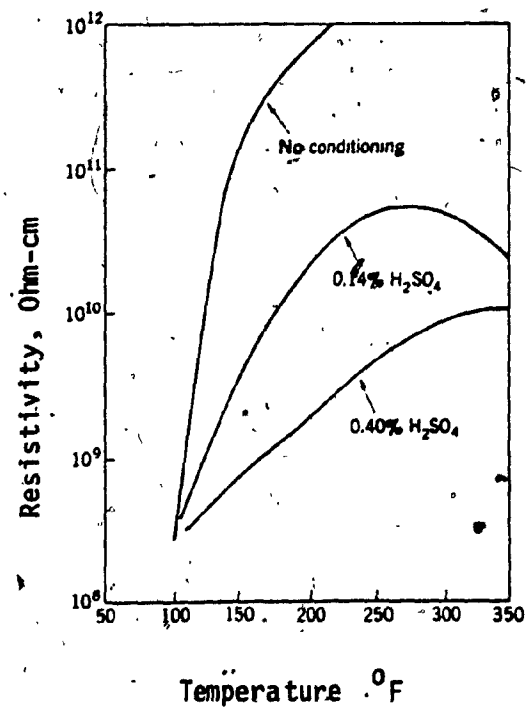


Figure 5.9 Effect of conditioning of fly ash by H_2SO_4 [71].

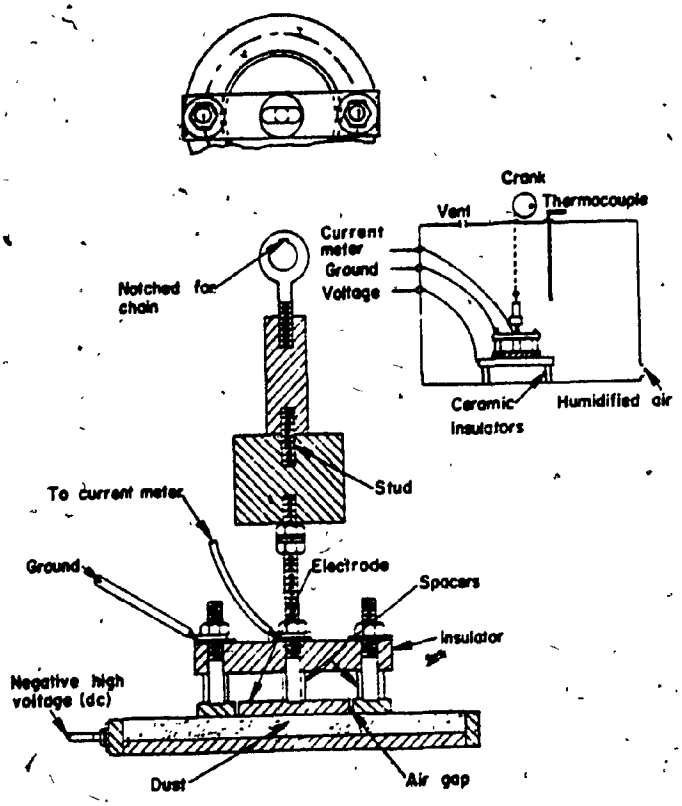


Figure 5.10 Bulk electrical resistivity apparatus [74].

The apparatus consists of a shallow cup which contains the dust, a disk and annular guard ring which rest on the dust samples, and a constant load on the measuring disk. The ash cup is supported by ceramic insulators and is connected to the negative terminal of a high voltage DC power supply. The annular guard ring is grounded and the center disk is grounded through a current meter. The positive

terminal of the power supply is connected to ground, and the entire test assembly is housed in a chamber suitable for temperature and humidity control. To measure resistivity, the dust specimen is placed in the sample cup and screened to give the proper thickness. The temperature and humidity in the chamber are brought to the desired conditions and the upper electrode assembly lowered to rest on the dust surface.

Voltage is then applied to the electrodes and gradually increased while the current and voltage are recorded up to the point of electrical breakdown of the dust layer. The resistance of the dust layer is calculated as the ratio of voltage to current just prior to breakdown. Resistivity can be computed as [75]

$$R = \frac{V}{J\ell} \tag{5.7}$$

where R is that dust resistivity, (Ω.m),

V is the voltage across the dust layer, (V),

J is the current density through the dust layer, (A/m^2)

and ℓ is the dust layer thickness, (m).

Different techniques in use for measuring dust resistivity with the associated apparatus are given by White [75].

5.7 GAS FLOW

The influence of the gas flow on over all precipitator performance is equivalent to that of the corona and the electrostatic forces acting on the particles. Disturbed flow in the form of excessive turbulence, jets or pulsations, not only causes reentrainment or blow-off of particles already captured from both electrodes and hoppers, but is responsible for poor collection downgrading precipitator collection efficiency. Other effects of poor gas flow are fallout or buildup of dust around turning vanes, elbows, and distribution plates. These conditions further alter the gas flow pattern, causing even less uniformity.

In zones of low gas velocity dust accumulates on the corona wires and buildups of one or two inches in diameter may occur [57]. These buildups tend to suppress the corona emission resulting in excessive sparking in some regions of the precipitator. On the other hand when gas velocity exceeds the critical value for the blow-off of collected particles severe reentrainment occurs. The reentrainment losses, due to the wide range of problems encountered in the field, cannot, in general, be calculated from theory, but must be determined empirically from measurements and observations.

For optimum precipitator performance, uniform gas flow with velocities of 5 to 6 ft/second must be maintained [48]. The Industrial Gas Cleaning Institute has recommended that gas flow be such that 85%

of the local velocities be within ± 25% of the mean flow velocity and that no single reading vary more than ± 40% from the average [76].

Techniques available for controlling and correcting gas flow patterns include mainly the use of guide vanes to change flow direction, flue transitions to couple flues of different sizes and shapes, and various types of diffusion screens and associated devices to reduce turbulence.

Gas flow in precipitators is extremely critical in the region near the hoppers. Dust rapped from the plates and falling into the hoppers creates a suspension of dust particles which would be carried out of the precipitator if high velocity gas flow were permited in the vicinity of the hoppers. To prevent or minimize gas flow through the hoppers, vertical transverse baffle plates are provided as shown in Fig. 5.11

Due to space limitations, the asymmetric and irregular shaped flues, mathematical and fluid dynamic design methods are difficult to implement. Design of precipitators should include gas flow model studies in critical cases. Experience shows that scale model laboratory studies are a very reliable and represent a practical approach to precipitator gas flow systems. Close correlation between model study results and field gasflow performance has been demonstrated by Burton and Smith [77].

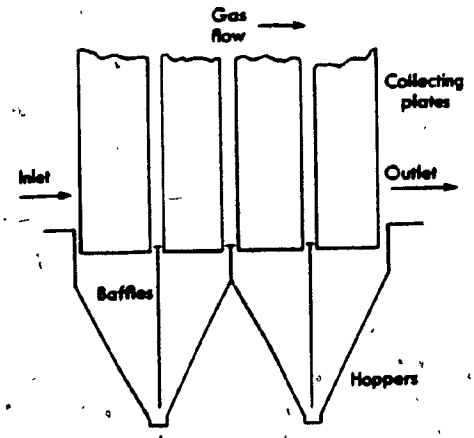


Figure 5.11 Schematic drawing of a hopper design [57].

CHAPTER VI

CONCLUSION

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6.1 SELECTION EVALUATION AND APPLICATION OF CONTROL DEVICES

The growing demand for energy coupled with a dwindling supply of relatively clean burning fossil fuels, has led to an increased utilization of lowgrade energy generating resources. In order to maintain an acceptable environment, this trend must be offset by the development of practical large scale air pollution control equipment. Particulates in the range of 0.1 to 1 μ represent the most critical environmental hazard. This particular size has been found to be the most effective vehicle for the introduction of objectionable substanses into the body and thereby seriously affecting the operation of the respiratory system [3]. The submicrometer particles are also the most difficult to remove from a gas stream.

At present, the electrostatic precipitator along with the fiber filter and the wet scrubber are the mechanisms most frequently used in pollution control problems. The selection of a control system is dictated primarily by the type of process emission and the quality of the emission needed to meet control objectives. Therefore, careful characterization of contaminants in an effluent stream and establishment of relevant specifications for the required removal efficiency, must precede the selection of equipment. Minimum removal efficiencies

of one or more components are normally stipulated by applicable local, provincial or national regulations.

For any pollution problem, there will generally be more than one control solution. Venturi scrubbers are particularly useful in those applications where sticky or combustible particulate matter is present or where corrosive gas streams are encountered. Because they operate at much higher velocities than baghouses or electrostatic precipitators (150 to 500 feet per second versus 5 to 15 feet per second), venturi scrubbers are physically smaller and can be economically manufactured by utilizing metal alloys or reinforced plastics which offer good resistance to corrosive gas streams. Particulate matter is collected in a noncombustible liquid (usually water) and all surfaces are wetted, thus preventing buildup of solids or any explosion hazard. Performance of venturi scrubbers and baghouses is independent of particle resistivity, and hence they can often be used in applications where electrostatic precipitators cannot. However scrubbers are relatively inefficient in view of the high energy input needed.

The fabric filter, especially the high energy fabric filter (e.g., pulse jet) gives inherently good removal efficiencies on fine particles. However its application is limited by the chemical and physical nature of the particles. Further the equipment cannot remove gaseous pollutants.

Electrostatic precipitators have been used extensively for many years to reduce industrial particulate emissions. These units handle very large gas volumes with low pressure drops. Precipitators are by far the largest single type of particulate removal device in terms of dollar volume because their primary application is in the utility industry for stack gas removal of fly ash. Some of the advantages of electrostatic precipitators in comparison with other control devices are: The system is dry, so corrosion or scalling is not usually a problem, the pressure drop through the precipitator, is low and the power requirement is low, and the equipment is relatively compact and maintenance and downtime are relatively low. Some of the disadvantages are: Performance depends on the chemical composition of the coal being burned, notably its sulfur content. Gas flow uniformity and reentrainment of particulates require attention to insure high collection efficiency. Capital equipment costs are relatively high.

Because of the extremely diverse range of applications and operating conditions it is difficult to derive a relative cost effectiveness standard for all control devices. In addition, installation constraints influence both capital and operating costs. Comparative cost data for typical installations at different collection efficiencies are shown in figure 6.1. J. McKenna, J. Mycock and W. Lipscomb [78] derived uniform economic comparisons between different particulate control techniques for a coal fired industrial

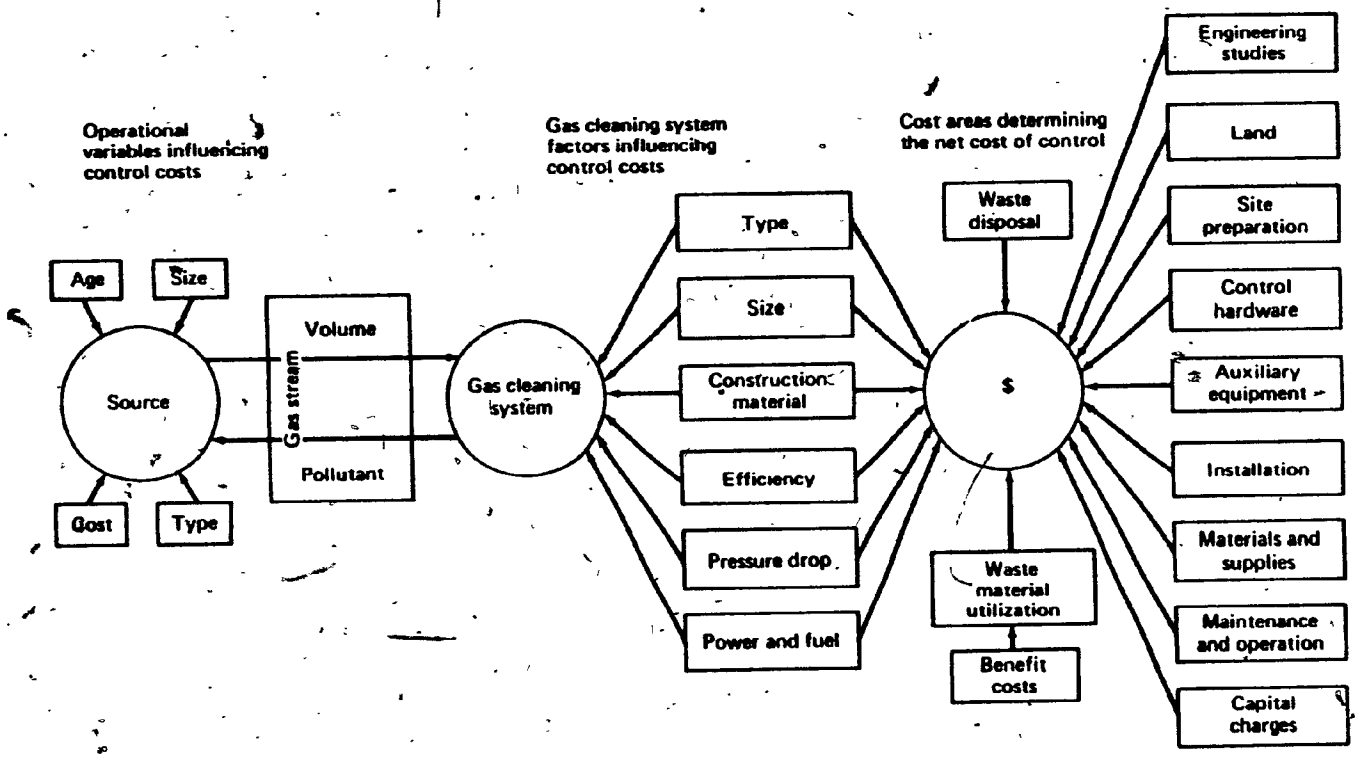

Figure 6.1 Diagram of cost evaluation scheme for a pollutant control system [82].

boiler. Their results are summarized in Figures 6.2, 6.3 and 6.4 which show capital, operating and annualized costs for electrostatic precipitation, wet scrubbing and fabric filtration at different efficiency levels. Although generalizations of the cost of fine particulate removal are inherently dangerous, it does appear, however, that only fabric filters and electrostatic precipitators are suitable to accomplish the particulate removal. Venturi scrubbing, because of the high energy required, does not compete economically.

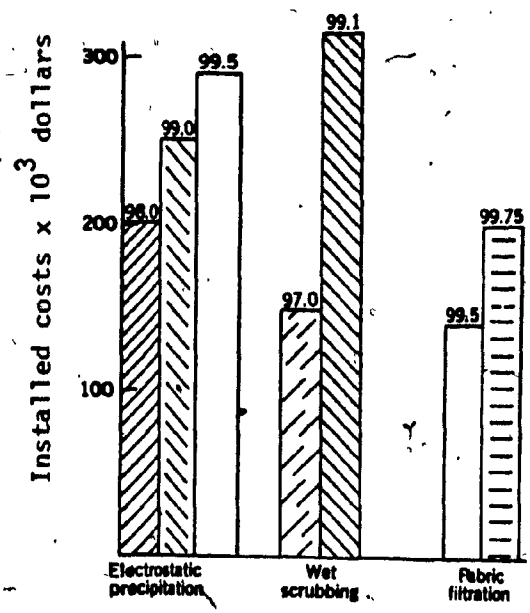

Figure 6.2 Installed cost comparisons at varying efficiencies.

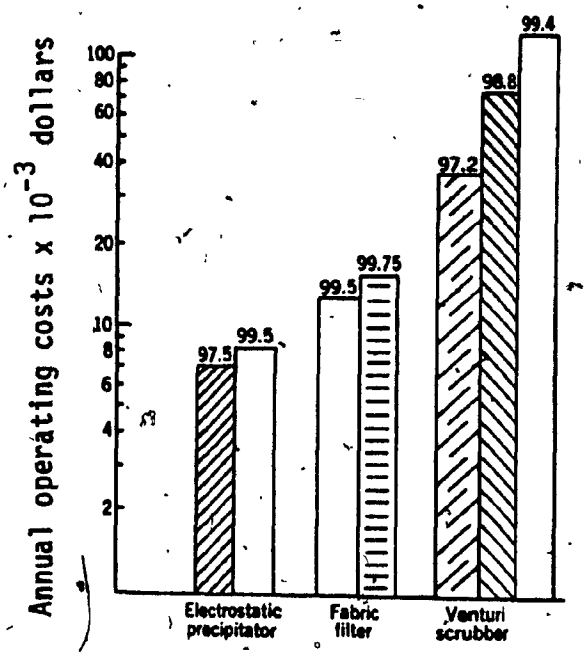

Figure 6.3 Operating cost comparisons for varying efficiencies.

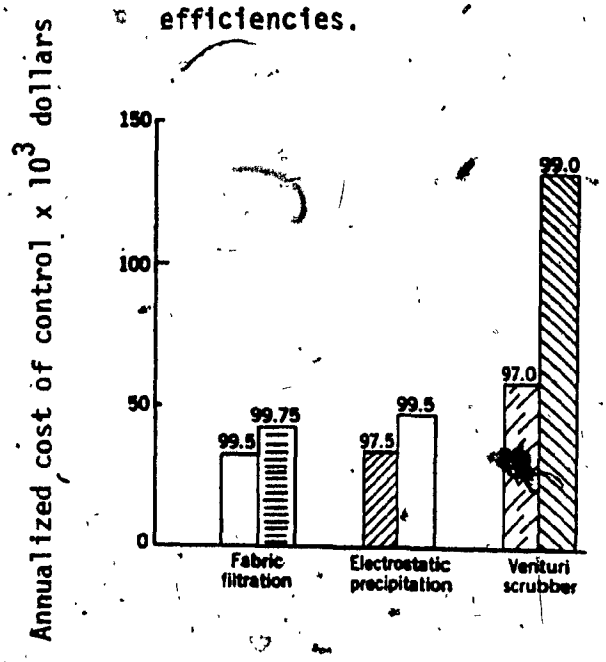

Figure 6.4 Annualized cost for varying efficiencies.

6.2 FUTURE TREND OF CONTROL DEVICES

Several new devices, which are claimed to be effective in the control of fine particulates have been reported in the literature [79, 80]. The most important is the wet electrostatic precipitator [81], which is already in limited production, while other devices are in the early stages of development. The wet electrostatic precipitator utilizes a continuous flow of finely divided liquid droplets, which become electrically charged and are attracted to the collecting plates. Precipitated water droplets create an evenly distributed water film which covers the entire collector surface. Solid particulates are charged and simultaneously attracted to the collecting surfaces and are captured by a continuously downward moving film of water. The water film on each of the collecting plates and discharge electrodes flow by gravity into a slurry through for convenient disposal. The wet electrostatic precipitator overcomes many of the limitations of the high energy scrubber, dry electrostatic precipitator, and the fabric filter, and its use can be generalized to applications where particles to be removed are solid and condensable, matter in the sub-micron range, and where gaseous pollutants also must be removed. The wet electrostatic power consumption, in terms of equivalent pressure drop, in approximately the same as for a fabric filter. This is normally in the range of 4 to 6 inches of water, well above the pressure drop of 0.5 inches of water for the dry electrostatic precipitator.

Demand for coal as a power generation source will determine the future growth of electrostatic precipitators. Such growth would include not only new power plants but retrofit units for older plants that must meet environmental regulations. In addition, increased use of low sulfur coals will require larger and a more expensive type of devices. Other markets could include application to coal conversion systems to remove particulates. In the industrial market, precipitators are being applied on a wet basis to obtain results given by wet scrubbers [81]. Fabric filters will continue to expand in the process industry as material recovery becomes more important and also as pollution standards are more rigidly enforced. The fact that submicron removal generally is not possible and that a water pollution problem exists limits the growth opportunities for wet scrubbers in particulate removal. Wet scrubbers are the primary piece of equipment for sulfur oxide abatement, and this application will account for the bulk of growth in the future.

Studies show that despite the existence and development of a number of control devices, the choice of basic processes for the effective removal of fine particles from gases is essentially limited to fabric filters, scrubbers and electrostatic precipitators. The big majority of control devices installed in the last few years, and that will be installed in the next 10 years is one of these three types [6].

REFERENCES

REFERENCES

1. W. Bach, A. Daniels, "Handbook of Air Quality in the United States", The Oriental Publishing Co., Honolulu, 1975.

2. J. Burchard, "Significance of Particulate Emissions", J. Air poll. Control Assoc., Vol. 25, no. 2, pp. 99-101, February 1975.

3. B. Jennings, "Environmental Engineering, Analysis and Practice", Int. Textbook Co., 6th Edition, p. 715, 1970.

4. M. Dean High, "Status Report on Federal Regulations for New Source Performance Standards", J. Air Poll. Control Assoc., Vol. 26, no. 5, p. 571, May 1976.

5. Environment Canada, "Air Pollution Emission and Control Technology. Metallurgical Coke Manufacturing Industry", Economic and Technical Review Report EPS 2-AP-74-6 Air Poll. Control Directorate, November 1974.

6. G. Benson, M. Smith, "Air Pollution Control, The State of the Art", Heating, Piping, Air Conditioning, Vol. 21, p. 45, December 1976.

7. M. Griggs, C. B. Ludwig, "Legal Aspects of Remote Sensing and Air Enforcement", J. Air Poll. Control Assoc., Vol. 26, no. 2, p. 119, February 1978.

8. Environment Canada, "Air Pollution Emission and Control Technology. Metallurgical Coke Manufacturing Industry", Economic and Technical Review Reports EPS 3-AP-74-6, Air Poll. Control Directorate, November 1974.

9. R. Ross, "Air Pollution and Industry", Van Nostrand, Reinhold Co., N.Y., p. 79, 1972.

10. "The Clean Air Act Annual Report, 1974-1975", Information Canada Cat. no. En. 41-1975, May 1975.

11. G. W. Walsh, "Emission Standards for Particulates", J. Air Poll. Control Assoc., Vol. 25, no. 2, p. 101, February 1975.

12. W. Beery, "Report on the Fourth APCA Government Affairs Seminar the Clean Air Act: Its Influence on Growth", J. Air Poll. Control Assoc., Vol. 26, no.7, p. 635, July 1976.

13. W. Bach, "Atmospheric Pollution" McGraw Hill Inc., N.Y., 1972.

14. C. Flodin, "Specification and Selection of Dust and Fume Collection Equipment", Consulting Engineer, Vol. 15, no.5, p. 245, May 1961.

15. W. Hemeon, "Gas Cleaning Efficiency Requirement for Different Pollutants", J. Air Pol. Control Assoc., Vol. 12, p. 105, January 1962.

16. Manual of "Airtemp, Electronic Air Cleaner", Airtemp Division, Chrysler Co., Model 3404-00, page 2.

17. R. A. Gussman, A. M. Sacco, "Design and Calibration of a High Volume Cascade Impactor", J. Air Poll. Control Ass., Vol. 23, no. 9, p. 778, September 1973.

18. W. Faith, A. Atkisson, "Air Pollution", Wiley Interscience, N. Y., p. 101, 2nd Edition 1972.

19. G. Herdan, "Small Particle Statistics: Measurement, Interpretation and Application", Butterworth London, 2nd Edition, p. 102, 1960.

20. J. McCrone, P. Draftz, R. Ronald, J. Delly, "The Particle Atlas", Science Publishers, Ann Arbor, Michican 1967.

21. M. Crawford, "Air Pollution Control Theory", McGraw Hill Inc., p. 123, 1976.

22. R. Lee, S. Goranson, "Cascade Impactor Network", Environmental Protection Agency", Research Triangle Park, North Carolina, Publication No. AP-108, July 1972.

23. A. Randolph, M. Larson, "Theory of Particulate Processes", Academic Press, N. Y., 1971.

24. S. Miyamoto, H. Bohn, "Filtration of Airborne Particulates by Gravel Filters: Collection Efficiency and Pressure Drop in Filtering Fume", J. Air Poll. Control Assoc., Vol. 25, no. 1, p. 40, January 1975.

in Filtering Fume", J. Air Poll. Control Assoc., Vol. 25, no. 1. p. 40, January 1975.

25. A. Stern, "Air Pollution", Academic press, N.Y., vol. II, p. 234, 1962.

26. W. Strauss, "Industrial Gas Cleaning", Pergamon Press, London, p. 144, 1966.

27. R. D. Ross "Air Pollution and Industry", Van Nostrand Reinhold Co., New York, p. 362, 1972

28. R. N. Payton, "Innovations in Ferroalloy Baghouse System Design", J. Air Poll. Control Assoc., Vol. 21, no. 1, p. 18, January 1976.

29. M. Sitting, "Particulates and Fine Dust Removal, Processes and Equipment", Noyes Data Corp. New Jersey, p. 486, 1977.

30. M. G. Kennedy, P. N. Cheremisinoff, "Air Pollution Control and Design Handbook", Part I, Marcel Dekker Inc., N.Y., p. 317, 1977.

31. J. Marchello, "Control of Air Pollution Sources", Marcel Dekker Inc., N.Y., p. 486, 1976.

32. R. E. Frey, "Types of Fabric Filter Installation", J. Air Poll. Control Assoc., Vol. 24, p. 1148, December 1974

33. American Industrial Hygiene Association, "Air Pollution Manual", Part 2, Detroit, Mich., p. 47, 1968.

34. Mikropul Corporation, Bulletin RD-1, Submit, N.J., 1971.

35. J. S. Eckert, R. F. Strigle "Performance of Wet Scrubbers on Liquid and Solid Particulate Matter", J. Air Poll. Control Assoc., Vol. 24, no. 10, p. 961, October 1974.

36. M. J. Pilat, A. Prem, "Effect of Diffusiophoresis and Thermophoresis on the Overall Particle Collection Efficiency of Spray Droplet Scrubbers", J. Air Poll. Control Assoc., Vol. 27, no. p. 982, October 1977.

37. H. E. Hesketh, "Fine Particle Collection Efficiency Related to Pressure Drop, Scrubbant and Particle Properties, and Contact Mechanism", J. Air Poll. Control Assoc., Vol. 24, no. 10, p. 939, October 1974.

38. S. C. Yung, H. F. Barbarika, S. Calvert, "Pressure Loss in Venturi Scrubbers", J. Air Poll. Control Assoc., Vol. 27, No. 4, p. 348, April 1977.

39. J. I. Acoortt, A. L. Plymbey, J. R. Martin, "Fine Particulate Removal and SO_2 Absorption With a Two Stage Wet Scrubber", J. Air Poll. Control Assoc., Vol. 24, no. 10, p. 967, October 1974.

40. S. Calvert, "Engineering Design of Fine Particle Scrubbers", J. Air Poll. Control Assoc., Vol. 24, no. 10, p. 929, October 1974.

41. S. W. Behie, "Effects of Water Injection Arrangement on the Performance of a Venturi Scrubber", J. Air Poll. Control Assoc., Vol. 24, no. 10, p. 943, October 1974.

42. S. Calvert, "Scrubbing" from Stern's "Air Pollution" 3rd Edition, Academic Press, N.Y., p. 271, 1977.

43. H. E. Hesketh, "Atomization and Cloud Behavior In Venturi Scrubbing", J. Air Poll. Control Assoc., Vol. 23, no. 7, p. 600, July 1973.

44. P. N. Cheremisinoff, R. A. Young, "Air Pollution Control and Design Handbook", Part 2, Marcel Dekker Inc., N.Y., p. 760, 1977.

45. R. F. Brown, A. B. Walker, "Feasibility Demonstration of Electrostatic Precipitation at 1700°F", J. Air Poll. Control Assoc., Vol. 21, no. 10, p. 617, October 1971.

46. R. Ross, "Air Pollution and Industry", Van Nostrand, Reinhold Co., N.Y., p. 397, 1972.

47. P. Cheremisinoff, R. Young, "Air Pollution Control and Design Handbook", Part I, Marcel Dakker Inc., N.Y., p. 386, 1977.

48. H. J. White, "Electrostatic Precipitation of Fly Ash" J. Air Poll. Control Assoc., Vol. 27, no. 1, p. 18, January 1977.

49. R. J. Heinsohn, S. H. Levine, R. J. Fjeld, G. W. Malamud", "Radiation Charging: A novel Way to Charge Fine Particles Electrically", J. Air Poll. Control Assoc., Vol. 25, no. 2, p. 179, February 1979.

50. F. W. Peek, "Dielectric Phenomena in High Voltage Engineering", 3rd Edition, McGraw-Hill, N.Y., 1929.

51. L. B. Loeb, "Electrical Coronas", University of California Press, Berkeley, 1965.

52. H. J. White, "The Role of Corona Discharge in the Electrical Precipitation Process", Electrical Engineering, Vol. 71, p. 67, January 1952.

53. R. G. Dorman, "Dust Control and Air Cleaning", Pergamon Press, N.Y., p. 280, 1974.

54. S. R. Hanna, "A Simple Method of Calculating Dispersion from Urban Area Sources", J. Air Poll. Control Assoc., Vol. 21, no. 12, p. 775, December 1971.

55. P. Cooperman, "A New Technique for the Measurement of Corona Field Strength and Current Density in Electrical Precipitation", Trans. Am. Inst. Elect. Engrs., Part I, Vol. 75, p. 64, March 1956.

56. P. Cooperman, "A Theory for Space Charge Limited Currents with Application to Electrical Precipitation", Trans. Am. Inst. Elect. Engrs., Part I, Vol. 79, p. 47, January 1960.

57. H. J. White, "Industrial Electrostatic Precipitation", Addison-Wesley Inc., Massach., p. 115, 1963.

58. G. B. Nichols, "Particulate Emission Control from Pulp Mill Recovery Boilers with Electrostatic Precipitators", IEEE Trans. Ind. Applic., Vol. IA-13, no. 1, p. 74, Jan-Feb. 1977.

59. B. Y. J. Liu, H. C. Yeh, "On the Theory of Charging of Aerosol Particles in an Electric Field, J. Applied Physics, Vol. 39, no. 3, p. 1396, February 1968.

60. G. W. Hewitt, "The Charging of Small Particles for Electrostatic Precipitation", Trans. Amer. Inst. Elec. Engrs., Part I, Vol. 76, p. 300, July 1957.

61. H. J. White, "Industrial Electrostatic Precipitation", Addison-Wesley Inc., Massach., p. 169, 1963.

62. G. Penney, "Some Problems in the Application of the Deutsch Equation in Industrial Electrostatic Precipitation", J. Air Poll. Control Assoc., Vol. 19, no. 8, p. 596, August 1969.

63. D. Selzler, W. Watson, "Hot versus Enlarge Electrostatic Precipitation of Fly Ash", J. Air Poll. Control Assoc., Vol. 24, no. 2, p. 115, February 1974.

64. N. T. Sproull, "Minimizing Rapping Loss in Precipitators at a 2000 Megawatt Coal Fired Power Station", J. Air Poll. Contr. Assoc., Vol. 22, no. 3, p. 181, March 1972.

65. W. T. Sproull, "Fundamentals of Electrode Rapping in Industrial Precipitators", J. Air. Poll. Control Assoc., Vol. 15, no. 1, p. 50, January 1965.

66. H. J. White, "Electrostatic Precipitation of Fly-Ash", J. Air Poll. Control Assoc., Vol. 27, No. 2, p. 114, February 1977.

67. R. E. Bickelhaupt, "Electrical Volume Conduction in Fly Ash", J. Air Poll. Control Assoc., Vol. 24, no. 3, p. 251, March 1974.

68. K. J. McLean, "Electrical Conduction in High Resistivity Particulate Solids", Ph.D. Thesis, University of New South Wales, Kensington, New South Wales, Kensington, New South Wales, Australia, 1969.

69. R. E. Wright, "The Application of Electrostatic Precipitators for the Control of Container Glass Emissions", IEEE Trans. on Industry Appl., Vol. 11, no. 4, p. 447, July-August 1975.

70. H. J. White, "Chemical and Physical Particle Conductivity Factors in Electrical Precipitation", Chem. Eng., Vol. 52, p. 244, March 1956.

71. W. E. Archer, "Electrostatic Precipitator Conditioning Techniques", Power Engineering, Vol. 76, no. 12, p. 50, December 1972.

72. R. L. Labbe, "Acid Conditioning of Metallurgical Smoke for Cottrell Precipitation", J. Metals, Trans. Amer. Inst. Mining Eng., Vol. 188, p. 692, July 1950.

73. J. S. Lagarias, "Fly Ash Resistivity Technology", J. Air Poll. Control Assoc., Vol. 28, no. 1, p. 23, January 1978.

74. American Society of Mechanical Engineers, "Determining the Properties of Fine Particulate Matter", Power Test Code 28, New York, 1965.

75. H. J. White, "Resistivity Problem in Electrostatic Precipitation", J. Air Poll. Control Assoc., Vol. 24, no. 4, p. 314, April 1974.

76. Industrial Gas Cleaning Institute, "Criteria for Performance Guarantee", Publication E-P3 3 .

77. C. L. Burton, D. A. Smith, "Precipitator Gas Flow Distribution", J. Air Poll. Control Assoc., Vol. 25, no. 2, p. 139, Feb. 1975.

78. J. D. McKenna, J. C. Mycock, N. O. Lipscomb, "Performance and Cost Comparisons Between Fabric Filters and Alternate Particulate Control Techniques", J. Air Poll. Control Assoc., Vol. 24, no. 12, p. 1144, December 1974.

79. D. C. Drehmel, "Fine Particle Control Technology: Conventional and Novel Devices", J. Air Poll. Control Assoc., Vol. 27, no. 2, p. 138, February 1977.

80. B. N. Cooper, R. Wang, D. P. Anderson, "Evaluation of Eight Novel Fine Particle Collection Devices", Report PB-251, 621, Environmental Protection Agency, Research Triangle Park, N. C., February 1976.

81. E. Bakke, "Wet Electrostatic Precipitators for Control of Submicron Particles", J. Air Poll. Control Assoc., Vol. 25, no. 2, p. 163, February 1975.

82. J. P. Stevens Company, "Selecting Fabrics for Filtration and Dust Collection", New York, 1961.

83. American Air Filter Company: Bulletin 310B Louisvilly, Ky., 1973.

APPENDIX I

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ANALYSIS OF AVAILABLE FABRICS [82].

Acrylics - A man-made fiber composed of long-chain polymers of at least 85 percent acylonitrile.

Specific gravity: 1.12 to 1.18

Tensile strength: 40,000 psi

Resistance to:

- Temperature: 275°F maximum for prolonged use; burns readily
- Acids: very good
- Alkalies: poor
- Oxidizing agents: fair
- Organic solvents: excellent
- Abrasion: good, but less than polyesters, polamides, and polypropylene
- Aging: excellent

Trade names: Orlon (Du Pont); Acrilan (Chemstrand); Creslan (American Cyanamid); Zefran (Dow Chemical); Crylor (Rhodiaceta); Dralong T (Farbenfabriken Bayer A. G.)

Comments: Common applications include filtration of ferrous and nonferrous metals, carbon black, cement, lime, fertilizers, food products, sand, and coal.

Cotton - A natural vegetable fiber.

Resistance to:

Temperature: 225°F maximum for prolonged use

Acids: poor (mineral acids); good (organic acids)

Alkalies: good

Oxidizing agents: fair

Organic solvents: excellent

Abrasion: fair

Aging: poor in comparison with synthetics

Comments: Cotton's ready availability and low cost have made it most popular for simple, low-temperature applications.

Glass - A fusion of silica sands, limestone, soda ash, and borax.

Specific gravity: variable

Resistance to:

Temperature: 500°F maximum for prolonged use (600°F surge); considered uncombustible

Acids: excellent

Alkalies: poor

Oxidizing agents: excellent

Organic solvents: excellent

Abrasion: poor

Aging: excellent

Trade names: Famco Fiber (Famco); Fiverglas (Owens-Corning); Fiber Glass (Johns-Manville)

Comments: Because of the poor abrasion resistance of glass, it is rarely, if ever, used in pulse-jet or reverse-jet collectors.

Nomex (Polyamide) [15] - A man-made fiber consisting of aromatic polyamide linked structures.

Specific gravity: 1.38

Resistance to:

Temperature: 450°F maximum for prolonged use

Acids: very good

Alkalies: very good

Oxidizing agents: poor

Organic solvents: excellent

Abrasion: excellent

Aging: excellent

Trade names: Nomex (Du Pont)

Comments: Nomex is the standard material for almost all high-temperature applications.

Nylon (polyamide) - A man-made fiber composed of recurring amide groups as an integral part of the polymer chain.

Specific gravity: 1.14

Resistance to:

Temperature: 250°F maximum for prolonged use

Acids: poor

Alkalies: good

Oxidizing agents: good, expect for high concentrations

Organic solvents: good, expect for some phenolic compounds

Abrasion: excellent

Aging: excellent

Trade names: Nylon 6 (Allied Chemicals, Enka, and Firestone);
Nylon 6.6 (Du Pont, Celanese, and Chemstrand)

Comments: Nylon is the most abrasion-resistant synthetic fiber.

Polyester - A man-made fiber composed of at least 85 percent ester of dihydric alcohol and terephthalic acid.

Specific gravity: 1.35 to 1.38

Tensile strength: 80,000 psi

Resistance to:

Temperature: 275°F maximum for prolonged use

Acids: good, except to anitric, sulfuric, and carbolic acids

Alkalies: good at moderate concentrations

Oxidzing agents: good

Organic solvents: excellent

Abrasion: excellent; second only to nylon

Aging: excellent

Trade names: Dacron (Du Pont); Vycron 2.5 (Beaunit Fibers); Enka Polyester (American Enka Corporation); Fortrel (Celanese); Kodel (Eastman)

Comments: The good overall qualities and relative low cost of this fabric make it the standard for filter media for many collector manufacturers.

Polypropylene (olefin) - A man-made fiber in which the fiber-forming substance is a long-chained polymer composed of at least 85 percent ethylene, propylene, or other olefin units.

Specific gravity: 0.90 to 0.91

Tensile strength: 110,000 psi

Resistance to:

Temperature: 180°F maximum for prolonged use

Acids: excellent

Alkalies: good

Oxidizing agents: good

Organic solvents: good, except for ketone, esters, aromatic and aliphatic hydrocarbons

Abrasion: excellent

Aging: excellent

Trade names: Herculon (Herculues Powder); Amerfil (American Thermoplastic); D L P (Dawbarn); Tufflite-P (Industrial Plastics)

Comments: Polypropylene is the most inexpensive synthetic fabric for filtration.

Teflon (fluorocarbon) - A man-made fiber produced from the homopolymer polytetrafluoroethylene. Monofilament yarn is made from the copolymer tetrafluoroethylene and hexafluoropropylene.

Resistance to:

Temperature: 450°F maximum for prolonged use

Acids: excellent

Alkalies: excellent

Oxidizing agents: excellent

Organic solvents: excellent

Abrasion: poor

Aging: excellent

Trade names: Teflon (Du Pont)

Wool - A natural animal fiber.

Resistance to:

Temperature: 200°F maximum for prolonged use

Acids: fair

Alkalies: poor

Oxidizing agents: poor

Organic solvents: fair

Abrasion: good

Aging: Weakens with age; susceptible to microorganisms

Fabric costs vary between manufacturers, but the following table reflects the average cost relationship among the various fabrics [16].

Material	Relative cost
Polypropylene	1.0
Polyamides	1.5 to 2.5
Acrylics	1.5 to 2.5
Polyesters	2.0 to 3.0
Cotton	2.5 to 3.5
Wool	2.5 to 3.5
Glass	2.5 to 3.5
Nomex	3.0 to 5.0
Teflon	20.0 to 25.0

APPENDIX II

APPENDIX II

BAGHOUSE TYPICAL AIR-TO-CLOTH RATIOS [83].

Dust	Usual air-cloth ratio (cfm/ft^2)		
	Shaker collector	Pulse-jet	Reverse-air collapse
Alumina	2.5-3.0	8-10	-
Asbestos	3.0-3.5	10-12	-
Bauxite	2.5-3.2	8-10	-
Carbon black	1.5-2.0	5-6	1.1-1.5
Coal	2.5-3.0	8-10	-
Coca, chocolate	2.8-3.2	12-15	-
Clay	2.5-3.2	9-10	1.5-2.0
Cement	2.0-3.0	8-10	1.2-1.5
Cosmetice	1.5-2.0	10-12	-
Enamel frit	2.5-3.0	9-10	1.5-2.0
Feeds, grain	3.5-5.0	14-15	-
Feldspar	2.2-2.8	9-10	-
Fertilizer	3.0-3.5	8-9	1.8-2.0
Flour	3.0-3.5	12-15	-
Graphite	2.0-2.5	5-6	1.5-2.0
Gypsum	2.0-2.5	10-.2	1.8-2.0
Iron ore	3.0-3.5	11-12	-

Dust	Usual air-cloth ratio (cfm/ft^2) Shaker Collector	Pulse-jet	Reverse-air collapse
Iron oxide	2.5-3.0	7-8	1.5-2.0
Iron sulfate	2.0-2.5	6-8	1.5-2.0
Lead oxide	2.0-2.5	6-8	1.5-1.8
Leather dust	3.5-4.0	12-15	-
Lime	2.5-3.0	10-12	1.6-2.0
Limestone	2.7-3.3	8-10	-
Mica	2.7-3.3	9-11	1.8-2.0
Paint pigments	2.5-3.0	7-8	2.0-2.2
Paper	2.5-4.0	10-12	-
Plastics	2.5-3.0	7-9	-
Quartz	2.8-3.2	9-11	-
Rock dust	3.0-3.5	9-10	-
Sand	2.5-3.0	10-12	-
Sawdust (wood)	3.5-4.0	12-15	-
Silica	2.3-2.8	7-9	1.2-1.5
Slate	3.5-4.0	12-14	-
Soap, detergents	2.0-2.5	5-6	1.2-1.5
Spices	2.7-3.3	10-12	-
Starch	3.0-3.5	8-9	-
Sugar	2.0-2.5	7-10	-
Talc	2.5-3.0	10-12	-

Dust	Usual air-cloth ratio (cfm/ft^2)		
	Shaker Collector	Pulse-jet	reverse-air collapse
Tabacco	3.5-4.0	13-15	-
Zinc oxide	2.0-2.5	5-6	1.5-1.8

Note: Values tabulated are based on light to moderate loadings of granular dust having particle size and shape characteristics typical of the specific material. Ratios will normally be less when dust loading is very heavy, temperature is elevated, or particle size is smaller than commonly encountered.