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Environmental Protection Technology Series

EPA FINE PARTICLE SCRUBBER SYMPOSIUM (SAN DIEGO, 5/28-30/74)

Office of Research and Development
U.S. Environmental Protection Agency
Washington, DC 20460

EPA-650/2-74-112

EPA FINE PARTICLE SCRUBBER SYMPOSIUM (SAN DIEGO, 5/28-30/74)

by

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CONTENTS

	Page
Technical Program	iv
Foreword	vi
Symposium Objectives	vii
Papers	
"Fine Particulates--The Misunderstood Air Pollutant"	1
"Engineering Design of Fine Particle Scrubbers"	12
"Submicron Particulate Scrubbing with a Two Phase Jet Scrubber"	33
"Performance of a Steam-Ejector Scrubber"	54
"Performance of Wet Scrubbers on Liquid and Solid Particulate Matter"	68
"Rotating Concentric Homogeneous Turbulence Gas Scrubber"	82
"Mean Drop Size in a Full Scale Venturi Scrubber Via Transmissometer"	91
"Fine Particle Collection Efficiency Related to Pressure Drop, Scrubbant and Particle Properties and Contact Mechanism"	109
"Effects of Water Injection Arrangement on the Performance of a Venturi Scrubber"	128
"Fine Particulate Removal and SO_2 Absorption with a Two-Stage Wet Scrubber"	144
"Flux Force/Condensation Scrubbing"	161
"Flux Force Condensation Aspirative Wet Scrubbing of Sub-Micron Particles"	194
"Entrainment Separators for Scrubbers"	207
"Future Needs for Fine Particle Scrubber Capabilities"	229
Panel Discussion	231
Closing Comments	240
List of People Attending the E.P.A. Symposium	242

TECHNICAL PROGRAM

WEDNESDAY, MAY 29, 1974:

Morning Session Chairman, John K. Burchard

9:00 - 9:05	Welcome to Symposium Seymour Calvert
9:05 - 9:20	Symposium Objectives Alfred B. Craig
9:20 - 9:50	Keynote Paper - "Fine Particulates-- The Misunderstood Air Pollutant" Richard E. Harrington
9:50 -10:00	Discussion
10:00-10:30	"Engineering Design of Fine Particle Scrubbers" Seymour Calvert
10:45-11:15	"Submicron Particulate Scrubbing with a Two Phase Jet Scrubber" H. E. Gardenier
11:15-11:45	"Performance of a Steam-Ejector Scrubber" L. E. Sparks, J. D. McCain, and W. B. Smith
11:45-12:15	Discussion

Afternoon Session Chairman, Gary J. Foley

1:45 - 2:15	"Performance of Wet Scrubbers on Liquid and Solid Particulate Matter"
2:15 - 2:45	"Rotating Concentric Homogeneous Turbulence Gas Scrubber" William C. Leith
2:45 - 3:00	Discussion
3:00 - 5:00	Panel Discussion Moderator - Leslie E. Sparks Panel Members - Harold H. Haaland Charles W. Lear Robert C. Lorentz J. R. Martin Jack E. Phelan Alexander Weir, Jr.

THURSDAY, MAY 30, 1974:

Morning Session Chairman, Charles E. Lapple

9:00 - 9:30	"Mean Drop Size in a Full Scale Venturi Scrubber Via Transmissometer" R. H. Boll, L. R. Flais, P. W. Maurer, and W. L. Thompson
9:30 -10:00	"Fine Particle Collection Efficiency Related to Pressure Drop, Scrubbant and Particle Properties and Contact Mechanism" Howard E. Hesketh
10:00-10:30	Discussion
10:45-11:15	"Effects of Water Injection Arrangement on the Performance of a Venturi Scrubber" S. W. Behie and J. M. Beeckmans
11:15-11:45	"Fine Particulate Removal and SO_2 Absorption with a Two-Stage Wet Scrubber" J. I. Accortt, A. L. Plumley and J. R. Martin
11:45-12:15	Discussion

Afternoon Session Chairman, James H. Abbott

1:45 - 2:15	"Flux Force/Condensation Scrubbing" Seymour Calvert and Nikhil C. Jhaveri
2:15 - 2:45	"Flux Force Condensation Aspirative Wet Scrubbing of Sub-Micron Particles" Stanley R. Rich and T. G. Pantazelos
2:45 - 3:15	"Entrainment Separators for Scrubbers" Seymour Calvert, I. Jashnani and S. Yung
3:45 - 4:15	"Future Needs for Fine Particle Scrubber Capabilities" Michael J. Pilat
4:15 - 4:45	"Expression of Air Pollution Control Association Interest" Harold M. Englund
4:45 - 5:00	Closing Remarks Dennis C. Drehmel

FOREWORD

Fine particles have come to be recognized as being much more significant air pollutants than particles larger than several microns diameter. The removal of fine particles from effluent gas stream is, unfortunately, more difficult than that of large particles. Because wet scrubbers are one of the major types of air pollution control equipment which can collect fine particles, it is important to define and exploit their potentialities.

To meet this need a symposium on the subject of fine particle scrubbing was sponsored by A.P.T., Inc. and the U.S. Environmental Protection Agency. It emphasized the collection of fine particles in any type of wet collector possible including hybrid devices. The objective was to stimulate and generate new and novel ideas for fine particulate control and promote interchange of ideas among scrubber experts.

Invited papers which contained significant new data and a panel discussion exploring new concepts were presented during two days of technical presentations and discussions. These proceedings are being furnished to the attendees, who included the users and the developers of new scrubber technology.

The Symposium organization committee members were:

SEYMOUR CALVERT, General Chairman - President, A.P.T., Inc., Riverside, California

JAMES H. ABBOTT, Program Committee - Chief, Particulate Technology Section, Environmental Protection Agency, Research Triangle Park, North Carolina

DENNIS C. DREHMEL, Program Committee - Control Systems Laboratory, Environmental Protection Agency, Research Triangle Park, North Carolina

PHYLLIS Z. CALVERT, Symposium Coordinator - A.P.T., Inc., Riverside, California

SYMPOSIUM OBJECTIVES

by

Alfred B. Craig

Environmental Protection Agency
National Environmental Research Center
Office of Research and Development
Control Systems Laboratory
Research Triangle Park, North Carolina 27711

"Symposium Objectives"
by
Alfred B. Craig

The Control Systems Laboratory (CSL) of the Environmental Protection Agency has been developing improved technology for the control of particulate emissions from stationary sources for nearly ten years. Starting about three years ago, emphasis has been gradually shifted to the study of fine particulate which we define as solid or liquid particles less than about three microns in diameter. Rationale for this shift in emphasis will be covered in Mr. Harrington's Keynote Paper, the next on our program.

In an effort to increase interest in fine particulate control technology within private industry and academic circles, CSL has established the following series of symposia covering all facets of this subject:

1. SEMINAR ON ELECTROSTATICS AND FINE PARTICLES
   National Environmental Research Center
   Research Triangle Park, North Carolina
   September 6-7, 1973
2. SYMPOSIUM ON THE USE OF FABRIC FILTERS FOR THE CONTROL OF SUBMICRON PARTICULATES
   Boston, Massachusetts
   April 8-10, 1974
3. FINE PARTICLE SCRUBBER SYMPOSIUM
   San Diego, California
   May 28-30, 1974
4. SYMPOSIUM ON ELECTROSTATIC PRECIPITATORS FOR THE CONTROL OF FINE PARTICLES
   Pensacola, Florida
   September 30-October 2, 1974
5. GENERATION AND COLLECTION OF FINE PARTICLE SYMPOSIUM
   (Tentative)
   Spring, 1975

The basic objectives of each of these symposia have been to:

1. Bring together in one location many of the leading authorities in the subject field of technology;
2. Present a comprehensive series of technical papers covering the broader areas of the subject technology;
3. Establish a forum for in-depth discussions of all facets of the control of fine particulates by the subject technology;
4. Stimulate new ideas for the development of new or improved techniques for control of fine particulates.

A review of the list of attendees at this meeting and the program arranged by Dr. Calvert indicates that we should quite ably meet all of these objectives at this symposium covering the use of wet scrubbers for the control of fine particulates for stationary sources.

FINE PARTICULATES--THE MISUNDERSTOOD AIR POLLUTANT

by

R. E. Harrington, Director
Air Pollution Control Division
Office of Research and Development
Environmental Protection Agency

ABSTRACT

This paper examines the basis of concern for particulate as an air pollutant. It concludes that while the data base for quantitative assessment of health and welfare affects is inadequate, there is sufficient evidence to show that fine particulate is a serious air pollution problem that must be controlled. Scrubbers have unique potential for dealing with this problem. Conventional scrubbers, however, have limitations for efficient capture of fine particulate and therefore must be augmented to realize their full potential.

FINE PARTICULATES--THE MISUNDERSTOOD AIR POLLUTANT

by

R. E. Harrington, Director
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In the late 1950s and early '60s, there began a public awakening to the problem of air pollution. This increasing concern over the pollution of our air was stirred by the public awareness of the extremes to which water pollution had progressed in many of our rivers and lakes; by the increasing interests of air pollution as detectable by visible smog and harsh chemical odors; by the alarming rate of increase in the number of cities that were being added to the list of smog plagued cities and communities; and by specific incidents where ill health or even death could be traced to specific episodes of air pollution. We were in a period of our history in which our National attitude was characterized by an increasing awareness and concern over a wide range of domestic matters such as civil rights, increased recreational opportunities, a shorter work week, crime and ecology.

It isn't surprising then that the very real but little understood problem of air pollution control and the broader problem of environmental pollution control became a National issue in the middle and late '60s. It became a major issue in the political arena and finally culminated in the Clean Air Act of 1967 and its major amendment of 1970 which further strengthened the Act. In December of 1970 the Environmental Protection Agency was established. Equally important during this period, numerous ecology groups were either established or escalated to a new level of activity.

In retrospect, I believe that most would agree that this sequence of events has been beneficial. While history will probably show that there have been extremes of inaction, action, and over-reaction, these very extremes have served to help focus on the specifics of the problem and define areas where more information, data, technology or control are needed.

Upon analysis, it is clear that the single major problem limiting our rate and efficiency of attack on the air pollution control problem is the paucity of good data in almost all areas including the nature and source of pollutants, effects of pollutants, ability to control pollutants, and the economics of control. While considerable progress has been made over the past 5 years we have only scratched the surface.

Typical of the problem of inadequate information is the problem of particulate control. The initial approach to the particulate control problem was first to define any finely divided solid or liquid material emitted into the air as particulate. Second, assume that if we controlled the mass emission of particulate emissions to a specified level, it would provide adequate protection of public health and welfare. Third, we may observe that for the "average" particulate emission stream there is existing control technology to attain the prescribed degree of mass emission control. Missing from this rationale is any consideration of quality, compositional or receptor - particulate characteristics interface factors. Upon closer examination it becomes obvious that these factors are of major importance.

Perhaps the most important single factor is particle size. Large particles (over 5 microns) constitute the major mass fraction of most sources of emission and it is true that economical control equipment exists for their efficient control. Further, while these larger particles frequently represent a significant welfare problem by contributing to soiling, unsightly smoke plumes and light obscurance they are not a major health problem in that they tend to settle relatively quickly, and are more easily scrubbed from the atmosphere by rain and they are not able to penetrate the respiratory system. By far, the most important form of particulate air pollution is the fine particulate.

There are several reasons why fine particulates, defined as solid or liquid airborne aerosols less than three microns in diameter, are one of the most important forms of air pollutants. First, fine particulates usually occur as a fraction of a distribution of larger particulates. While coarser particulates are easily collected by conventional control equipment, fine particulate pass through with much lower efficiencies of collection. Further, the finer particulates emitted into the atmosphere remain airborne for extended periods. Second, their greater ability to obstruct light causes the limited visibility typical of air pollution haze and smog. Third, fine particulates are a health hazard, since in contrast to coarser particles, they can bypass the body's respiratory filters and penetrate deeply into the lungs. The chemical and physical characteristics of fine particulate can further aggrevate their health impact. Because of their high surface area, some fine particles have been identified as transport vehicles for gaseous pollutants, both adsorbed and reacted, and hence can produce synergistic effects deleterious to human health. Since many fine particulates are metallic materials, some are chemically and catalytically highly active.

Fine particulate air pollutants may be classified into two major classes based on their origin. These are (1) primary fine particulates which are emitted or immediately condensed as fine particulates from a specified source and (2) secondary fine particulates which are the products of atmospheric reactions. Water is excepted as an air pollutant except as it may occur as man-made ice fog.

Primary particulates typically result from physical or chemical processes, which may include condensation of gaseous products or products of chemical reactions. High temperature processes such as metallurgical operations and combustion of fossil fuels are major sources. Metallurgical operations represent major sources of metal fumes unique to the process, such as lead, zinc, arsenic, mercury, copper or iron oxide fumes. Combustion processes produce a spectrum of materials found as ash components of the fuels. Combustion of residual oil, for example, produces quantities of vanadium, chromium, nickel, iron, copper and other highly reactive and catalytic metals. Primary sources of fine particulates represent the principle source of these metallic constituents in the air. It has been theorized that these highly active and catalytic materials play a key role in the formation of secondary particulates by acting as catalysts in chemical and photochemical smog-forming processes.

Some processes emit solid and liquid hydrocarbon emissions such as organic condensibles, tars and carbon particles capable of sorption of more volatile constituents or gases. These emissions constitute another type of primary fine particulates. The processes from which these emissions come include pyrolysis, incomplete combustion, vaporization of lubricating or process oils, and many chemical processes such as textile, refinery, petrochemical and plastics production operations. Forest fires as well as controlled agricultural and slash burning also are sources of this category of fine particulates.

Secondary particulates result from atmospheric reactions between gaseous pollutants. Photochemical reactions requiring sunlight as a stimulus have been long known. Although they have been studied for several years, these reactions have been found to be complex and difficult to model. Some of these reactions result in condensible, solid or liquid state components or products that react readily with water to produce particulates. Since these secondary particulates are usually the product of gaseous reactions, they are seldom if ever the source of metallic particulates. Being anionic in nature, they can and probably frequently combine with metallic particulates to form salts.

There are no good data on the relative amounts of primary and secondary fine particulates in the atmosphere. Since both are almost exclusively the product of man-made pollution, they would be expected to vary significantly from site to site depending upon such factors as industry composition, fuel-use patterns, and climate and weather. It seems clear, however, that since both primary and secondary particulates are the results of emissions from human activity, the key to their control is to prevent their release or the release of their precursors to the atmosphere.

Basis of Concern for Fine Particulates

As is frequently the case with non-infectious pollutants and toxicants, the health effects case against fine particulates is not clear cut. First it must be remembered that fine particulates are not a single pollutant but a large category of pollutants with a common set of size, transport and behavioral characteristics. Once dispersed, fine particulates behave, depending upon their size, like something between a coarse particle and a gas. They remain suspended, diffuse, are subject to brownian motion, exhibit little inertial characteristics, follow fluid flow around obstacles, and like gas molecules can penetrate deeply into the respiratory system.

The moderate amount of information that is available concerning the deposition of particles in man and lower animals is based upon mathematical models and to a limited extent, experimental data obtained from man. Particles larger than 5 microns are deposited in the nasal cavity or nasopharynx. Increasing numbers of smaller particles are deposited in the lungs. Contrary to the often quoted position that particles less than about 0.2 microns enter the respiratory system and are subsequently exhaled, over 50% of the number of particles between 0.01 and 0.1 microns that penetrate into the pulmonary will be deposited. This ability of particulates to penetraté into the respiratory system and be captured is principally a function of their size and is almost completely independent of the chemical properties of the particle.

The health effects of fine particulates that have penetrated the respiratory system and been captured, on the other hand, is almost completely dependent on their chemical or toxic nature. It is, therefore, not possible to generalize on health effects of fine particulates; rather the health effects of specific materials must be considered. Here the data become sparce and it becomes necessary to draw on our knowledge of toxic characteristics of specific substances gained through other information sources and our understanding of physiological mechanisms that work to dispose of collected materials.

The principal means through which air pollutants exert an effect on health is through inhalation and direct effects on the respiratory system. They may result in short term irritant effects or longer term damage such as silicosis or asbestoses. In either case the respiratory system is directly impaired.

A second mechanism involves the respiratory system indirectly as a significant route of entry for non-respiratory toxicants. In this case, substances which are deposited in the respiratory system are translocated to the gastro-intestinal system by muco-cilliary transport and swallowed. They may then exert a primary toxic effect or be absorbed and translocated to other tissues where an adverse health effect might be elicited.

In addition to the chemical and toxic nature of the particulate, they have potential for causing adverse health effects dependent upon the solubility of the particle in the transport mucus; if highly soluble, particulates may cause toxic inflammation.

Particles deposited deep in the lungs may be cleared very slowly. In this case, the clearing is dependent upon particle solubility. The preponderance of evidence indicates that non-soluble particles remain deep in the lungs for long periods--weeks, months, even years. Thus, the carcinogenic hazard of long-lived radioactive metals and airborne chemicals; hydrocarbons are of special concern.

Because certain metals may be soluble in respiratory secretion, the toxic properties of these substances may be manifested in the lung or airways or may be translocated to other organs. Vanadium is one example of such a metal. Unfortunately, however, the minimum time concentration exposure of vanadium and other metals is not adequately known. Needless to say, the combined effects of multiple pollutants is also not adequately known.

Because of the present paucity of knowledge concerning the health effects of specific pollutants and combinations of pollutants, many years will be required to develop a data base to quantify the health effects problem of fine particulates. This quantitative understanding will come as our data base is enlarged through continued and expanded programs such as the EPA Community Health Environmental Surveillance Study (CHESS) program and studies of selected cities in the United States.

Sufficient information does exist, however, to conclude that fine particulates must be controlled if public health is to be protected. It is therefore essential that the research strategies for fine particulate control include a program of control technology development that will assure the ability of industry to prevent the release of primary particulates and the gaseous precursors of secondary fine particulates.

The need for control of fine particulate has only recently been recognized. We do not adequately understand it importance or effect on public health and welfare. We do not know what pollutants are most important or insidious or to what extent they should be controlled. We do recognize, however, that control is necessary.

Since this is a new problem the technology requirements for measurement and control are not yet assessed and developed. It is essential that we learn what level of control can be achieved with existing control technology, where existing systems can be applied, and what new technologies are needed. New, advanced, more economic methods are needed to fill the technological gaps.

Most conventional scrubbers, when used in the conventional way, have a limited capability for controlling fine particulate. This is because most conventional scrubbers depend on some form of inertial collection of particulate as their primary mechanism of capture. Because of this, collection efficiency decreases rapidly as particle size is decreased to the point where inertial forces become insignificantly small. As a result it becomes necessary to greatly increase the energy input into a scrubber to significantly improve its ability to collect smaller particulate. Even with large energy inputs their collection efficiencies in the sub-micron range is not good.

Scrubbers on the other hand have unique characteristics useful to fine particulate control. Since the particulate collection media is liquid the captured particle is trapped in such a way as to avoid reentrainment and can be easily removed from the collection device. Scrubbers also can be used with potentially explosive gases and high temperature gases where cooling of the gas is acceptable.

Beyond their normal mode of operation, scrubbers offer considerable potential for modification for use in fine particulate control. Scrubbers designed to make maximum use of filtration or electrostatic mechanisms may greatly extend their capability into the small particle region. Using the scrubber as a condensation device has already been demonstrated to significantly increase their fine particulate collection efficiency. Hybrids of these and other techniques such as sonics, foams, and fluidized beds may provide opportunities for needed break-throughs that will permit efficient and economic use of scrubbers for fine particulate control.

The principal reason why we do not today have all the instrumentation we would like for measuring particle size; adequate control devices for collection of fine particulate and adequate information on health effects is that prior to the past year or so, there has been no need for collecting fine particulates. The small amount of product lost, ash uncollected, or haze residual in discharge plumes was unimportant. It has now become important.

I am convinces that starting with a proper understanding of the problem and its priority we can develop the necessary technologies and data to deal with the problem. Many possible and some promising techniques have already suggested themselves. I am convinced that given a little time and the necessary resources the scientific community will rise to the challenge.

Key to achieving the objectives of defining and controlling the fine particulate air pollution problem is good information exchange. Seldom in modern times have major developments been made by one man or woman working by himself. Communication and the resultant exchange and cross pollination of ideas have been the key ingredient responsible for the exponential progress that has been made in the field of technology in the past 100 years of man's history. Symposia such as this with their papers, debates, questions and answers, negotiations and general dialog is a major form of this essential ingredient, communication.

This symposium has an impressive agenda, list of authors, participants and attendees. I urge you to take maximum advantage of this forum to learn, teach, test ideas and establish continuing working relationships and lines of communication and cooperation so that we can quickly, efficiently, and economically and profitably solve the problem of fine particulat control.

"ENGINEERING DESIGN OF FINE PARTICLE SCRUBBERS"

by
Dr. Seymour Calvert, President
A.P.T., Inc.

ABSTRACT

A concise, quantitative picture of the state of the art of particle scrubbing is presented in the form of performance prediction methods. A new relationship between the particle diameter collected at 50% efficiency and scrubber pressure drop for several of the most common scrubber types is a design tool of great utility. Scrubber capability for the collection of sub-micron particles by diffusion is described in a graph for several scrubber types.

"Engineering Design of Fine Particle Scrubbers"

by Dr. Seymour Calvert

President, A. P. T., Inc.

Wet scrubbers of appropriate type have the ability to collect fine particles (i.e., those smaller than 2.0 μm diameter) with high efficiency under the right conditions. This paper is an outline of the general capabilities of scrubbers and the circumstances under which they will perform at various levels of efficiency on fine particle collection. We will begin by noting the general types of scrubbers and the basic mechanisms by which particles can be separated from the gas phase.

Scrubbers may be classified according to their geometry, or their "unit mechanisms", or other characteristics. We prefer the first two, as given in the "Scrubber Handbook" (1972) and as summarized in Table I. Note that the unit mechanisms are the simple particle collection elements which account for the scrubber's capability.

Within any of the unit mechanisms the particles may be separated from the gas by one or more of the following particle deposition phenomena:

1. Inertial impaction
2. Interception
3. Brownian diffusion
4. Turbulent diffusion
5. Gravitational force
6. Electrostatic flux force
7. Diffusiophoretic flux force
8. Thermophoretic flux force
9. Magnetic flux force
10. Photophoretic flux force

TABLE I

Scrubber Classifications

Geometric Type	Unit Mechanism for Particle Collection
Plate	Jet impingement, bubbles
Massive packing	Sheets (curved or plane), jet impingement
Fibrous packing	Cylinders
Pre-Formed Spray	Drops
Gas Atomized Spray	Drops, cylinders, sheets
Centrifugal	Sheets
Baffle and Secondary Flow	Sheets
Impingement and Entrainment	Sheets, drops; cylinders, jets
Mechanically aided	Drops, cylinders, sheets
Moving Bed	Bubbles, sheets
Combinations	

The understanding and analysis of any scrubber can be reached by determining which combination(s) of unit mechanism and particle deposition phenomenon are involved. Once the basic elements of the scrubber are determined and their performance capabilities defined by mathematical equations or charts, the performance of the scrubber can be predicted. We will now turn to the discussion of the capabilities of scrubbers in present use; but first we must explain the way in which we will describe scrubber performance.

Difficulty of separation

The "cut diameter" method, first described in the "Scrubber Handbook" and further discussed by Calvert et al. (1974), will be used. This method is based on the idea that the most significant single parameter to define both the difficulty of separating particles from gas and the performance of a scrubber is the particle diameter for which collection efficiency is 0.5 (50%).

For inertial impaction, the most common particle separation process in presently used scrubbers, aerodynamic diameter defines the particle properties of importance.

$$d_{pa} = d_p \, (\rho_p \, C')^{1/2}, \text{ common units} = \mu m (g/cm^3)^{1/2} \equiv \mu mA \qquad (1)$$

When other separation mechanisms are important, other particle properties may be more significant but this will occur generally when "d_p" is less than a micron.

When a range of sizes is involved, the overall collection efficiency will depend on the amount of each size present and on the efficiency of collection for that size. We can take these into account if the difficulty of separation is defined as the aerodynamic diameter at which collection efficiency (or penetration) must be 50%, in order that the necessary overall efficiency for the entire size distribution be attained. This particle size is the required "separation cut diameter", "d_{RC}" and it is related to the required overall penetration, $\overline{Pt}$, and the size distribution parameters.

The number and weight size distribution data for most industrial particulate emissions follow the log probability law. Hence, the two well established parameters of the log-normal law adequately describe the size distributions of particulate matter. They are the geometric mean weight diameter "d_{pg}" and the geometric standard deviation "σ_g"

Penetration for many types of inertial collection equipment can be expressed as:

$$Pt = \exp \, (-A_a \, d_{pa}{}^{B}) \qquad (2)$$

We use the simplifying assumption that this relationship can be based on actual diameter, d_p. This will not introduce much error and it will conservatively utilize too low an efficiency for particles smaller than a micron or so. Thus:

$$Pt = \exp(-Ad_p^{\ B}) \tag{3}$$

Packed towers, centrifugal scrubbers, and sieve plate columns follow the above relationship. For the packed tower and sieve plate column "B" has a value of 2. For centrifugal scrubbers "B" is about 0.67. Venturi scrubbers also follow the above relationship and B ≈ 2 when the throat impaction parameter is between 1 and 10.

The overall (integrated) penetration, $\overline{Pt}$, of any device on a dust of any type of size distribution will be:

$$\overline{Pt} = \int_0^W \left(\frac{dw}{W}\right) Pt \tag{4}$$

The right-hand side of the above equation is the integral of the product of each weight fraction of dust times the penetration on that fraction. If equation (4) is solved for a log-normal size distribution and collection as given by equation (3), the resulting equation can be solved to yield Figures 1 and 2.

Figure 1 is a plot of "$\overline{Pt}$" vs. $(d_{p50}/d_{pg})^B$ with "B ln (σ_g)" as a parameter. For a required "$\overline{Pt}$" one can find the value of d_{RC} when "d_{pg}", "σ_g", and "B" are given. For convenience, Figure 2 is presented as a plot of "$\overline{Pt}$" vs. (d_{p50}/d_{pg}) with σ_g as the parameter when B = 2.

To illustrate the use of the separation cut diameter, assume that 2% penetration is needed for dust with d_{pg} = 10 μm, ρ_p = 3g/cm³ and σ_g = 3. If a scrubber such as a packed bed, sieve plate, or venturi is to be used, Figure 2 shows the cut diameter, d_{p50}, must be 0.09 x (d_{pg}) = 0.9 μm. The corresponding aerodynamic diameter is d_{RC} = 1.7 μm (g/cm³)$^{1/2}$ = 1.7 μmA. Of course if the scrubber is capable of a smaller cut diameter, that is good; so "d_{RC}" is the maximum cut diameter acceptable. Some scrubbers, such as venturis, are only approximately fitted by relating penetration to exp (d_p^2) and more accurate plots can be prepared by using more representative performance equations. To avoid confusion these will not be given here, although they are presented in the "Scrubber Handbook".

Scrubber Performance

Collection efficiencies have been reported in the form of "grade efficiency" curves, which are plots of particle collection efficiency versus particle diameter for "typical" scrubbers. Unfortunately, there can be great variation in performance, depending on operating conditions and scrubber geometry so that one would need a grade efficiency curve for each important set of parameters .

The cut diameter approach proves to be a much more compact way to characterize scrubber performance. We have applied it to a number of the important types of scrubbers and present performance graphs for them. It has the great virtue of being a single-number criterion with a wide range of quantitive validity. Capability is defined by "performance cut diameter", "d_{PC}", which is the aerodynamic particle diameter at which the scrubber gives 50% collection efficiency.

Once a scrubber type, size, and operating conditions are chosen by matching the "separation" and "performance" cut diameters, (i.e., $d_{RC} = d_{PC}$) a more accurate efficiency-diameter relationship can be developed and a more accurate computation of overall penetration can be made. The reason this step is necessary is that the relationship between overall penetration and separation cut diameter is shown in Figures 1 and 2 is only correct for packed beds and similar devices and is an approximation for others.

Spray Chamber Performance

A spray chamber consists essentially of a round or rectangular chamber into which water is introduced through one or more sprays. Drop size depends upon liquid pressure and the type of nozzle used. Some solutions of the equations for inertial collection in a counter-current spray chamber are plotted in Figure 3 as "d_{PC}", vs. column height, with drop diameter, air velocity and water to air ratio as parameters. Standard air and water properties have been used, so the figures can only be applied to cases where the gas and liquid properties approximate those. In the cross-flow case the water is sprayed at the top of the spray chamber while the gas flows horizontally. The predictions for inertial collection in a cross-current spray chamber are plotted in Figure 4.

The lack of uniformity in liquid distribution and the fraction of liquid hitting the walls will vary from one spray chamber to another and will introduce empirical correction factor. For small scrubbers the correction factor might be on the order of 0.2 to account for spray running down the walls, (i.e., use 0.2 x Q_L/Q_G actual.)

Venturi

Venturi scrubbers employ gradually converging, then diverging sections, although geometry does not seem to have an important effect on performance. Usually liquid enters the venturi upstream of the throat through nozzles. Alternately, the liquid may flow along the converging section walls until reaching the throat. At the throat, the liquid is shattered into droplets by the high velocity gas.

Venturi performance is shown in terms of its predicted aerodynamic cut size against gas velocity, with liquid to gas ratio as parameter, and with constant pressure drop lines indicated in Figure 5, based on mean drop diameter. A value of 0.25 for the empirical factor "f" has been used as is appropriate for hydrophobic particles and medium to high liquid to gas ratios. For hydrophyllic particles a value of 0.4 to 0.5 for "f" should be used.

Once one has computed the required separation cut diameter for a given application, he can find the approximate operating region from Figure 5 for hydrophobic particles. This does not tell the whole story however, because the penetration depends not only on the collection efficiency of a single drop but also on the extent to which the gas is swept by drops. In other words, the drop holdup (volume fraction drops) in the throat is a significant factor in determining particle penetration and it cannot be accounted for by a simple power relationship with particle diameter. Penetration reaches a limiting value as particle size increases even if the collection efficiency of one drop for that size particle approaches 100% when there are not enough drops to completely sweep the gas stream.

Plate and Packed Columns

Particle separation in sieve (perforated) plates can be defined mathematically by starting from the basic mechanisms of particle collection in bubbles and jet impaction and then correlating experimental data. Some examples of the performance predictions are given in Figure 6, a plot of aerodynamic cut diameter for a sieve plate as a function of air velocity through the holes, u_h, the froth density, F, and hole diameter, d_h. Predictions are given for wettable particles, froth densities of 0.4 and 0.65, and for standard air and water properties. Note that cut diameter is inversely proportional to froth density. Froth density must be predicted from relationships for sieve plate behavior.

Packings

Particle collection in packed columns can be described in terms of gas flow through curved passages and performance for a variety of packing shapes can be correlated simply by the packing diameter. Aerodynamic cut diameter is predicted as a function of packing diameter, d_c, bed depth, Z, and bed porosity, ε, for three different superficial air velocities and plotted in Figure 7. Any effect of liquid rate is neglected; this is on the conservative side since the available data indicate that efficiency increases with "Q_L"

SCRUBBER ENERGY

The energy required for particle scrubbing is mainly a function of the gas pressure drop, except for pre-formed sprays and mechanically aided scrubbers. Previously we have been shown that there is an empirical relationship between particle penetration and power input to the scrubber for a given scrubber and a specific particle size distribution (Lapple and Kamack (1955) and Semerau (1960)). However, this "power law" did not provide a way to predict performance vs. power input for any size dust, without first determining the relationship experimentally.

A new relationship, between "d_{PC}" and scrubber pressure drop, has been developed by the author and is presented here. Figure 8 is a plot of performance cut diameter, d_{PC}, versus gas pressure drop for sieve plates, venturi (and similar), impingement plates, and packed columns. Predictions were made by means of design methods given in the "Scrubber Handbook".

1. Sieve plate penetration and pressure drop predictions for one plate are plotted as lines 1a and 1b for perforation diameters of 0.5 cm and 0.3 cm, respectively, and F = 0.4. Cut diameters for other froth densities can be computed from the relationship that they are inversely proportional to "F". Cut diameters for two and three plates in series would be 84% and 80% of those for one plate at any given pressure drop. Note that these predictions are for wettable particles and that both froth density and pressure drop are dependent on plate design and operation.

2. Venturi penetration and pressure drop data are given for f = 0.25 and f = 0.5 in lines 2a and 2b, respectively. The predictions are for a liquid to gas ratio, $Q_L/Q_G \approx 1\ \ell/m^3$, corresponding to about the minimum pressure drop for a given penetration. Data recently obtained by A.P.T. for a large coal-fired power plant scrubber fit a value of f = 0.5.

3. Impingement plate data used for line #3 were predicted for one plate. Cut diameters for 2 and 3 plates in series are 88% and 83% of those shown in line #3.

4. Packed column performance as shown by line #4 is representative of columns from 1 to 3 meters high and packing of 2.5 cm nominal diameter.

To estimate the penetration for particle diameters other than the cut size, under a given set of operating conditions, one can use the approximation of equation (3) with B = 2.0. Alternatively, one could use more precise data or predictions for a given scrubber. Figure 9 is a plot of the ratio of particle aerodynamic diameter to cut diameter versus penetration for that size particle (d_{pa}), on log-probability paper. One line is for equation (3) and the other is based on data for a venturi scrubber.

Performance Limit for Inertial Impaction

The limit of what one can expect of a scrubber utilizing inertial impaction is clearly indicated by Figure 8. If a cut diameter of 1.0 μmA, or smaller is required, the necessary pressure drop is in the medium to high energy range. High efficiency on particles smaller than 0.5 μmA diameter would require extremely high pressure drop if inertial impaction were the only mechanism active.

High efficiency scrubbing of sub-micron particles at moderate pressure drop is possible, but it required either the application of some particle separation force which is not dependent on gas velocity or the growth of particles so that they can be collected easily. Particle separation phenomena which offer promise and have been proven to some extent are the "flux forces" due to diffusiophoresis, thermophoresis, and electrophoresis. Brownian diffusion is also useful when particles are smaller than about 0.1 μm diameter.

Particle growth can be accomplished through:

1. Coagulation (agglomeration)
2. Chemical reaction
3. Condensation on particles
4. Ultrasonic vibrations
5. Electrostatic attraction

Diffusional Collection

Particle collection by Brownian diffusion can be described by relationships for mass transfer and it is possible to outline the magnitude of efficiency which can be attained with typical scrubbers. The general relationship which describes particle deposition in any control device in which turbulent mixing eliminates any concentration gradient normal to the flow outside the boundary layer and in which the deposition velocity is constant is:

$$Pt = \exp - \left(\frac{u_{PD}\ A_d}{Q_G}\right) \tag{5}$$

The particle deposition velocity for Brownian diffusion, u_{BD}, can be estimated from penetration theory as:

$$u_{BD} = 1.13 \left(\frac{D_p}{\theta}\right)^{1/2} \tag{6}$$

For packed columns, the penetration time, θ, can be taken as the time required for the gas to travel one packing diameter. For plate scrubbers which involve bubbles rising through liquid, the penetration time for a circulating bubble is about that for the bubble to rise one diameter, as shown by Taheri and Calvert (1968). For spray scrubbers the penetration time is that for the gas to travel one drop diameter.

Predictions of particle penetration due to Brownian diffusion only were made by means of equations (5) and (6) for a typical sieve plate and packed columns. A prediction for a venturi scrubber was made by means of "Scrubber Handbook" equation (5.2.6-17), for gas phase controlled mass transfer.

The results are plotted on Figure 11 as collection efficiency vs. particle diameter. It can be seen that high efficiency collection of 0.01 μm diameter particles is readily attainable with a three plate scrubber, typical of a moderately effective device for mass transfer. Collection efficiency for particles a few tenths micron diameter is poor, as is well known.

Particle separation by flux force mechanisms is not amenable to such simple treatment as Brownian diffusion because of the variation of deposition velocity with heat and mass transfer rates within the scrubber. Since this topic is being covered by another presentation in this symposium, it will not be discussed further in this paper.

Summary and Conclusions

Wet scrubbers can collect fine particles with high efficiency under the proper circumstances. When particle collection is due to inertial impaction only, high efficiency on sub-micron particles requires the expenditure of high pressure drop. Other particle separation phenomena such as Brownian diffusion, diffusiophoresis, thermophoresis, and electrophoresis can give high efficiency at low pressure drop. Particle growth by any of several mechanisms can provide the means for subsequent high efficiency collection by inertial impaction.

The new relationship between particle cut diameter and scrubber pressure drop for collection by inertial impaction, which is presented here, provides a simple means for estimating scrubber performance. More refined predictions can be made by means of the performance cut diameter method.

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NOMENCLATURE

Latin

A = a constant in eq. (3)

A_d = total collection surface area in scrubber cm^2

B = a constant in eq. (3)

C' = Cunningham "slip" correction factor, dimensionless

d_b = bubble diameter, cm

d_c = packing diameter (nominal), cm

d_d = drop diameter, cm

d_h = sieve plate hole diameter, cm

d_p = particle diameter μm or cm

d_{p50} = diameter of particle collected with 50% efficiency μm

d_{pa} = aerodynamic particle diameter μmA

d_{PC} = performance cut diameter (aerodynamic), μmA

d_{pg} = geometric mean particle diameter, μm

d_{RC} = required separation cut diameter (aerodynamic), μmA

D_p = particle diffusivity, cm^2/sec

E = efficiency, fraction or %

f = empirical constant for sprays, dimensionless

F = foam density, g/cm^3

h = height of scrubber, cm

Pt = penetration = 1 - E, fraction or %

$\overline{Pt}$ = average (integrated over particle size distribution) penetration, fraction or %

ΔP = pressure drop, cm W.C. or atm.

Q_G = gas volumetric flow rate, m^3/sec

Q_L = liquid volume flow, m^3/sec or l/sec

u_{BD} = particle deposition velocity for Brownian diffusion, cm/sec

u_G = gas velocity relative to duct, cm/sec

u_h = gas velocity through sieve plate hole, cm/sec

u_{PD} = particle deposition velocity, cm/sec

w = weight of particles, g

W.C. = water column = pressure as measured by water manometer, cm

Z = height of packing or column, m or cm

<u>Greek</u>

ε = fraction void volume space

ρ_L = liquid density, g/cm^3

ρ_P = particle density, g/cm^3

σ_g = geometric standard deviation of particle size distribution

θ = penetration time, sec.

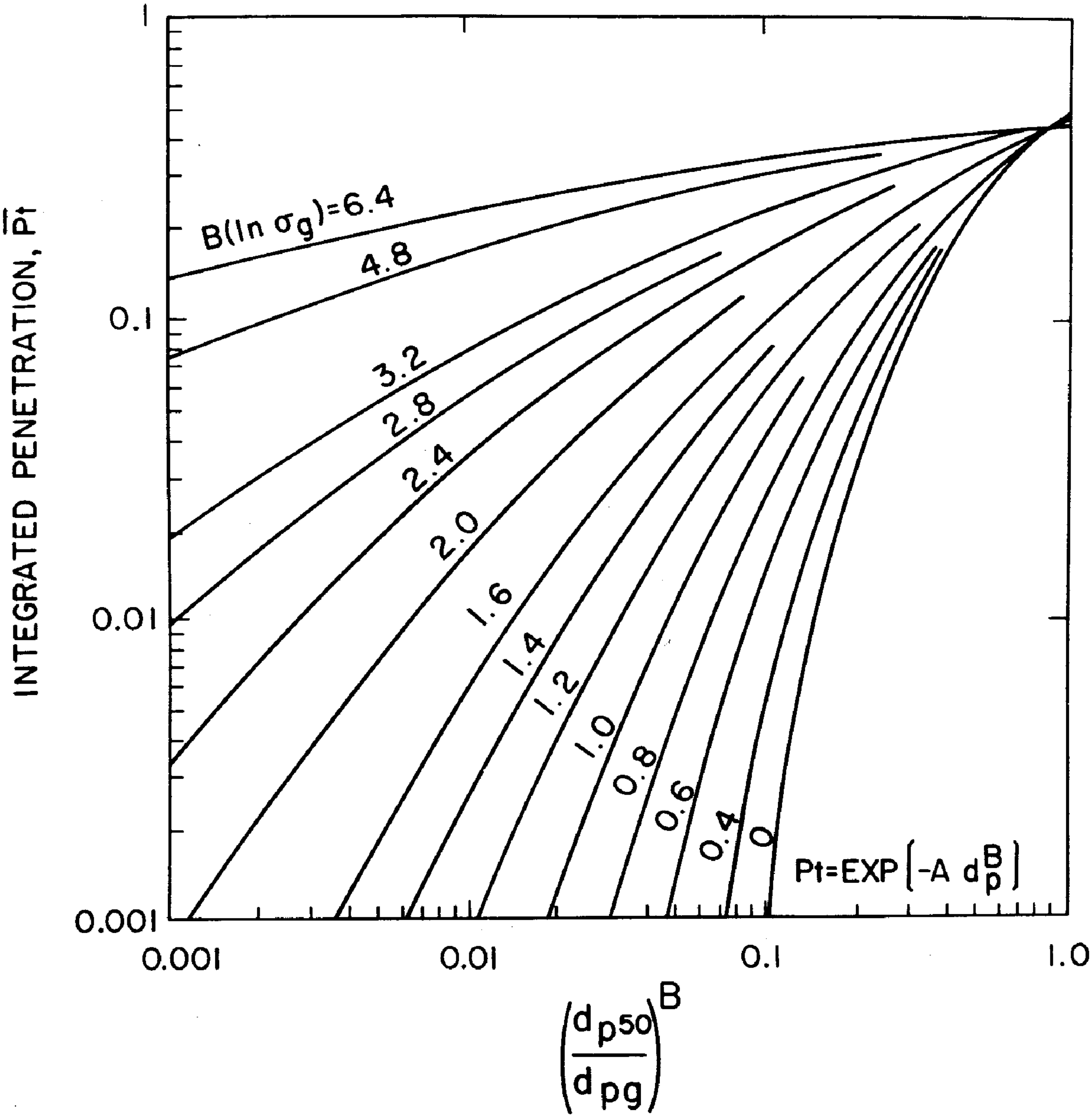


FIGURE 1. INTEGRATED (OVERALL) PENETRATION AS A FUNCTION OF CUT DIAMETER, PARTICLE PARAMETERS AND COLLECTOR CHARACTERISTIC.

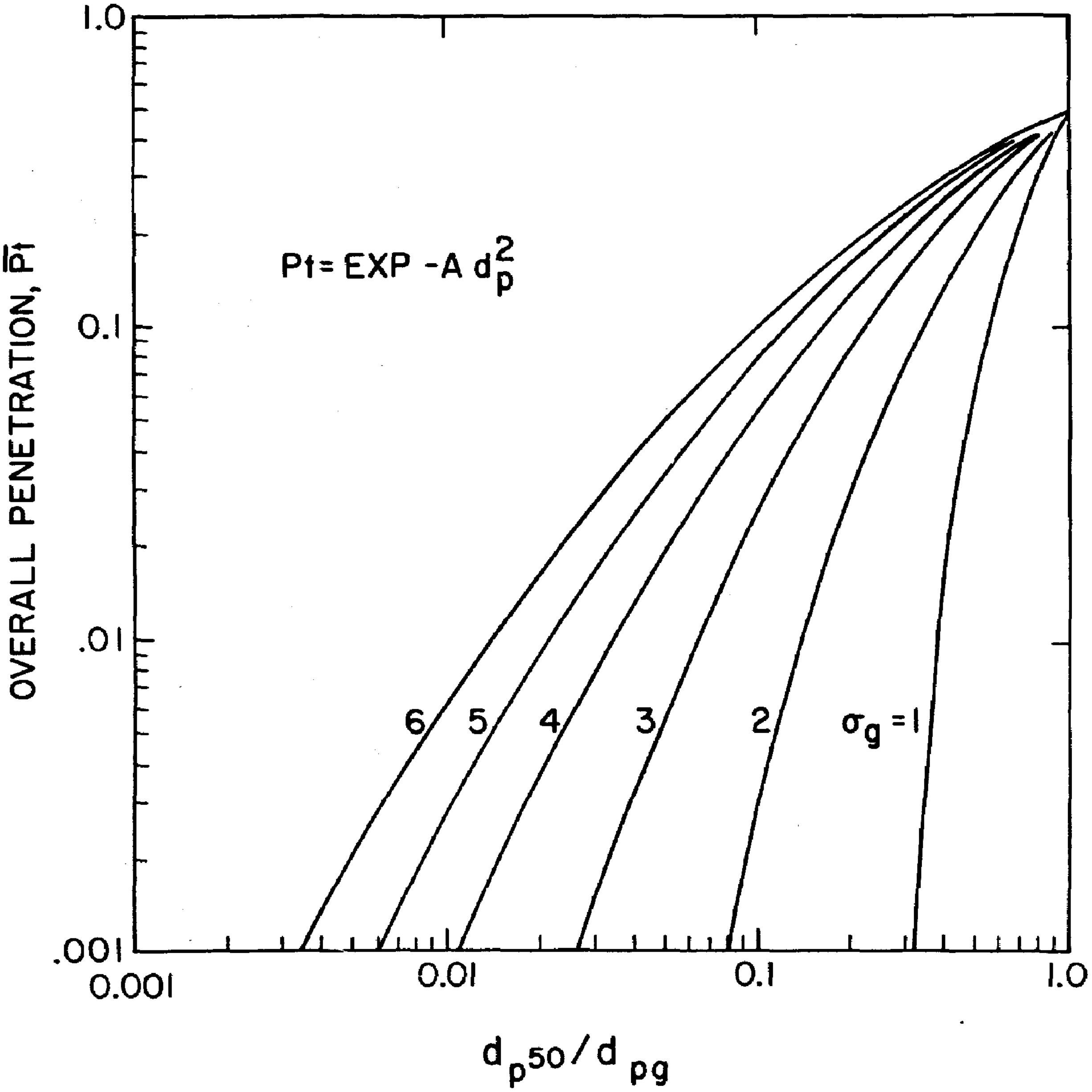
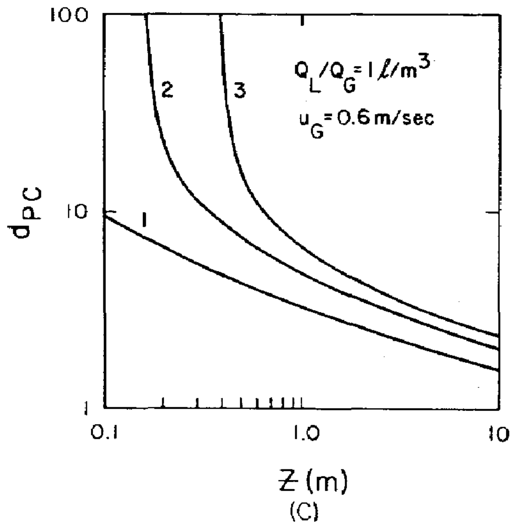


FIGURE 2
OVERALL PENETRATION AS A FUNCTION OF CUT DIAMETER AND PARTICLE PARAMETERS FOR COMMON SCRUBBER CHARCTERISTIC, B= 2.



CURVE NO.	1	2	3
DROP DIA, µm	200	500	1,000

FIGURE 3
PERFORMANCE CUT DIAMETER PREDICTIONS FOR
TYPICAL VERTICAL COUNTERCURRENT SPRAY.

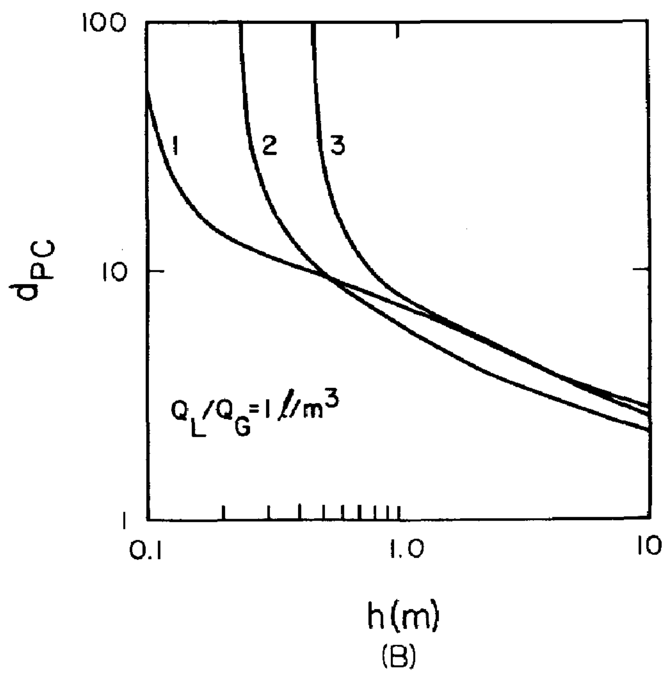


FIGURE 4
PERFORMANCE CUT DIAMETER PREDICTIONS
FOR TYPICAL CROSS-CURRENT SPRAY

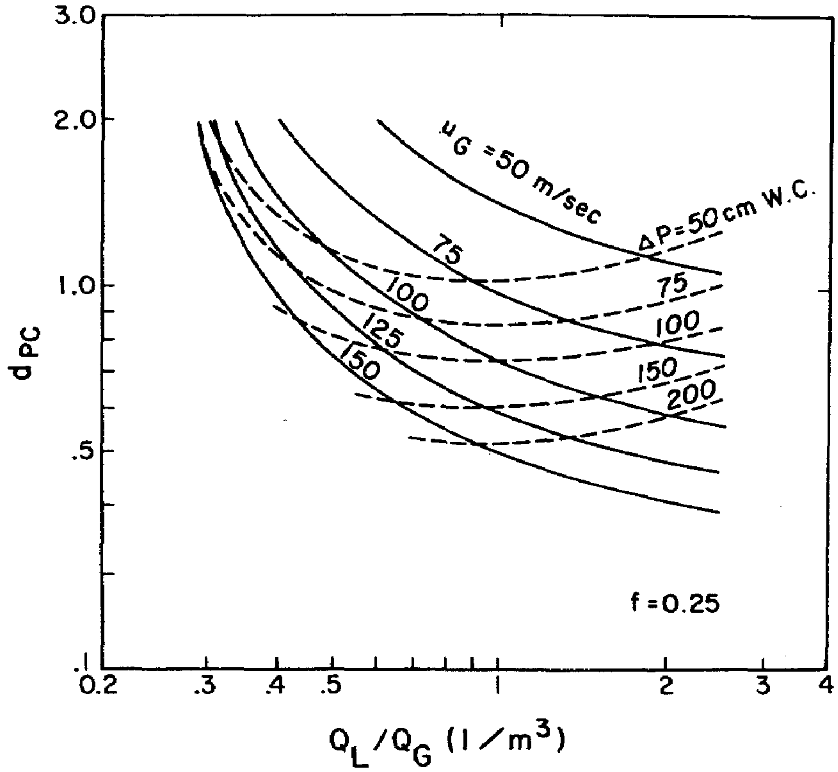


FIGURE 5
PERFORMANCE CUT DIAMETER PREDICTIONS FOR VENTURI SCRUBBER.

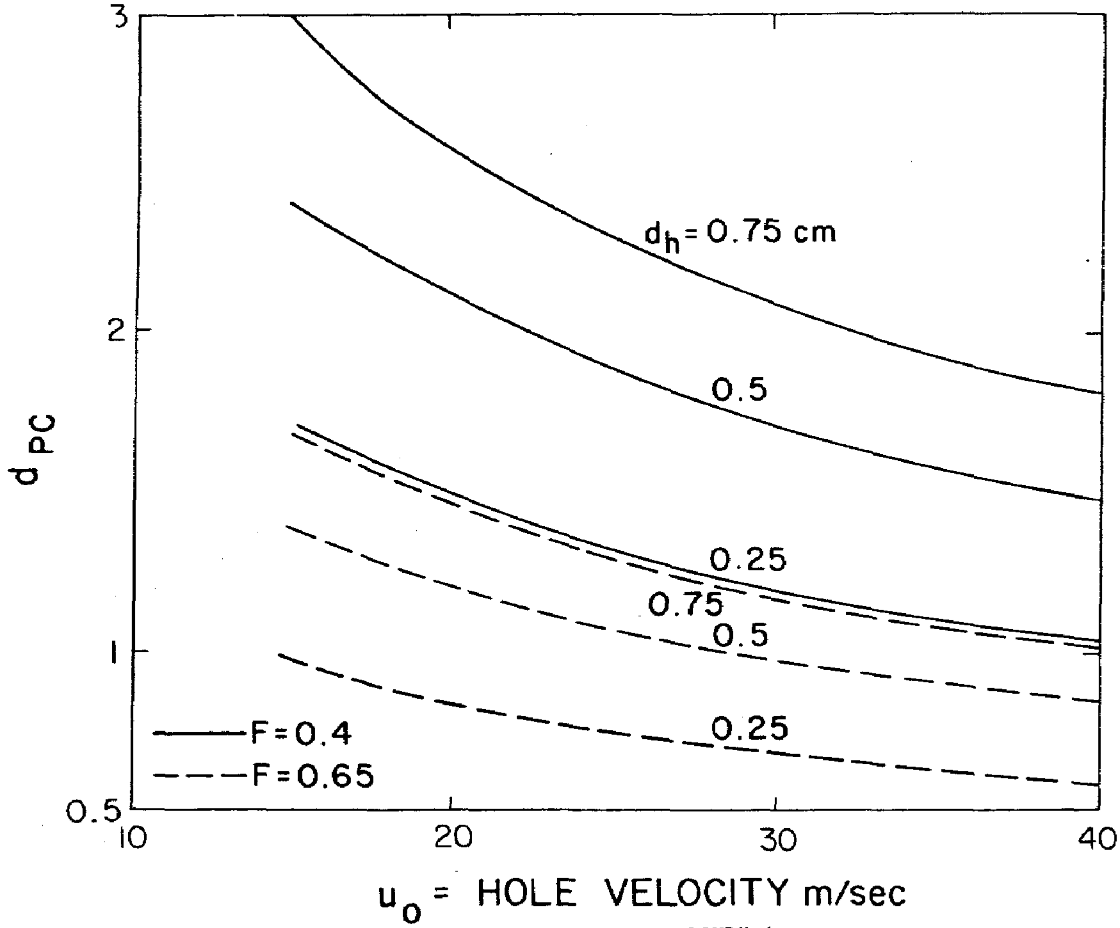


FIGURE 6
PERFORMANCE CUT DIAMETER PREDICTION FOR TYPICAL SIEVE PLATE CONDITIONS.

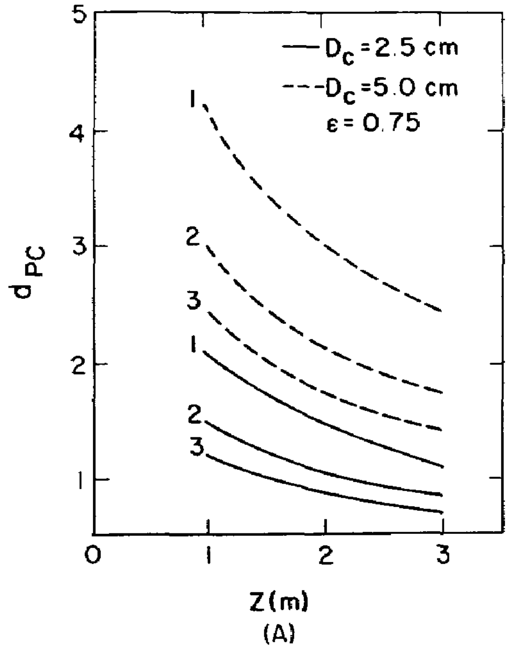


FIGURE 7
PERFORMANCE CUT DIAMETER PREDICTIONS FOR TYPICAL PACKED BED CONDITIONS.

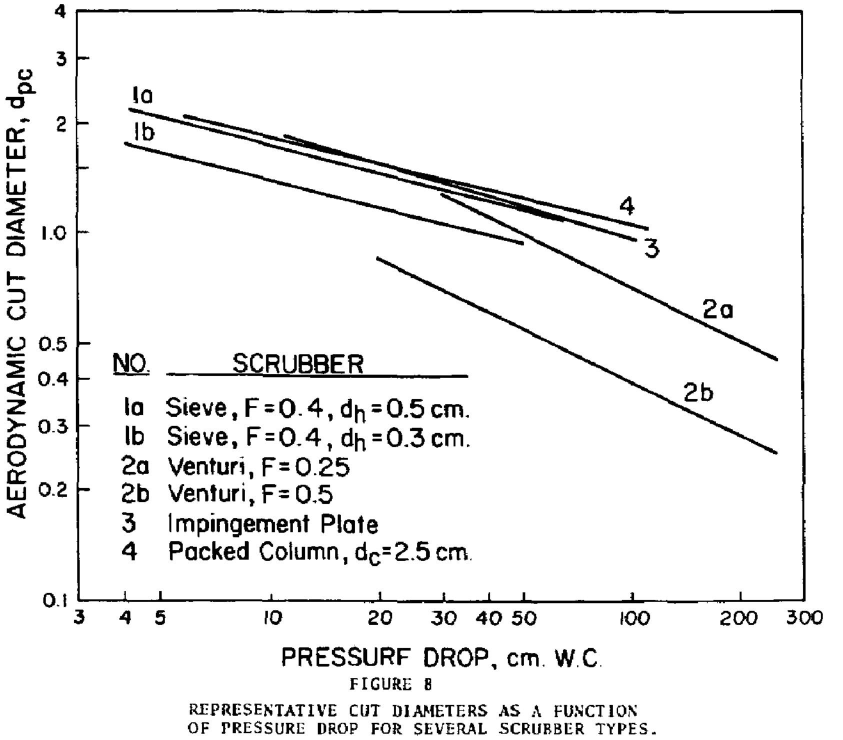


FIGURE 8
REPRESENTATIVE CUT DIAMETERS AS A FUNCTION OF PRESSURE DROP FOR SEVERAL SCRUBBER TYPES.

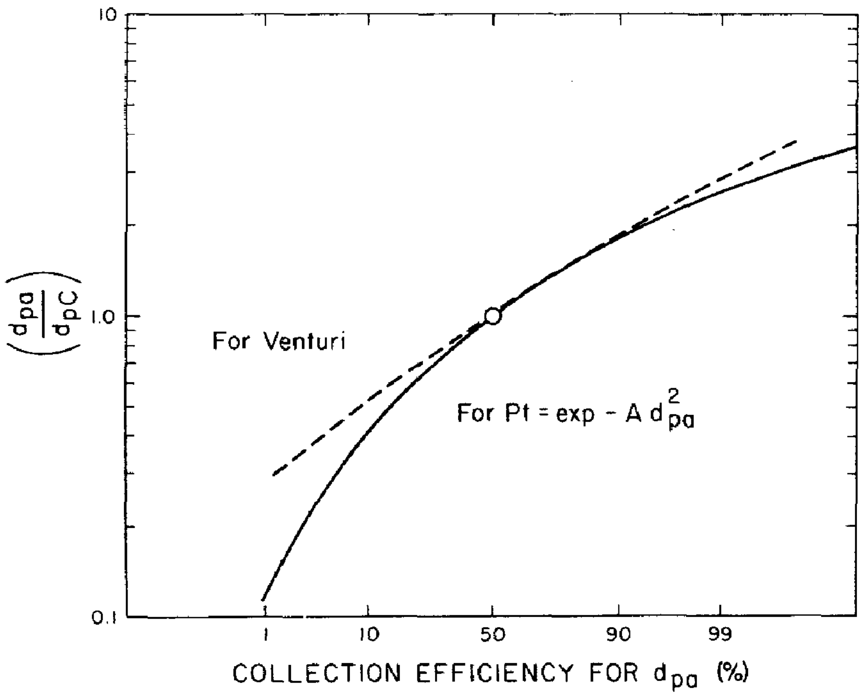


FIGURE 9
RATIO OF PARTICLE DIAMETER TO CUT DIAMETER AS A FUNCTION OF COLLECTION EFFICIENCY.

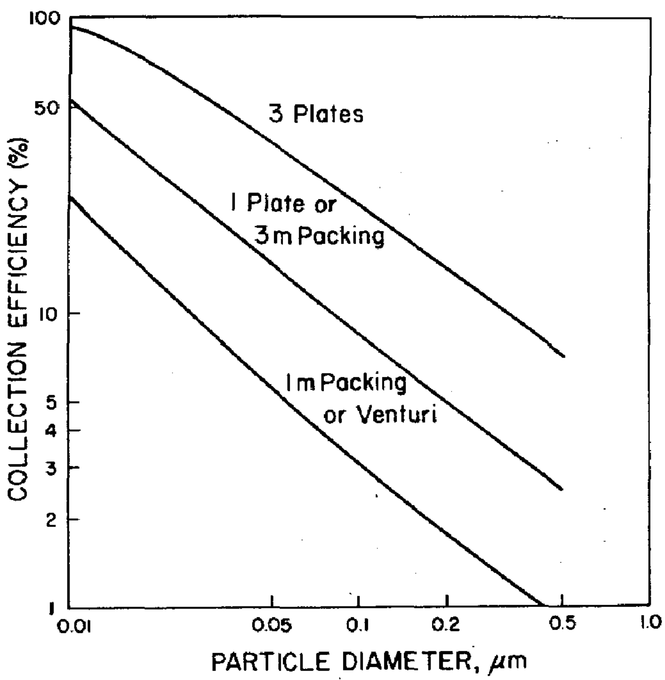


FIGURE 10
PREDICTED PARTICLE COLLECTION BY DIFFUSION IN PLATES, PACKING, AND VENTURI SCRUBBERS.

SUBMICRON PARTICULATE SCRUBBING
WITH A TWO PHASE JET SCRUBBER

by

H. E. Gardenier
Aronetics, Inc.
Houston, Texas

ABSTRACT

The two-phase jet scrubbing system utilizes waste thermal energy to provide the operating power for a two-phase jet which simultaneously cleans and induces the necessary draft. Test results have shown excellent cleaning performance and a substantially reduced operating cost.

"Submicron Particulate Scrubbing With a Two Phase Jet Scrubber"

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There are dozens of different types of devices which fall into the general classification of wet scrubber. However, only a very limited number of types of equipment are capable of efficiently removing submicron particulate. Much has been written regarding the actual mechanism by which solid particulate is entrained in a scrubbing fluid. Experts disagree regarding the predominant physical phenomena. In our view the primary mechanism is inertial impaction; condensation and Brownian movement are secondary effects which may improve the overall scrubber efficiency. For certain cases the solid particulate size approaches the molecule size of the carrier gas; as a result it becomes a very significant problem to provide contact between scrubber fluid droplets and the solid particulate. Providing the impact energy in an economical manner is indeed a challenging task.

If a scrubber is to have reasonable water requirements and yet provide a high probability of contact between the liquid droplets and the solid particulate there must be a very fine atomization of the scrubbing liquid. This provides a high population density of droplets and a good probability of collision between particles and droplets. The inertial impaction energy must come from a difference in velocity between the droplet and the solid particulate. Either high velocity particulate must be introduced into a finely atomized scrubbing fluid, or a high velocity, finely atomized scrubbing fluid must be introduced into the particulate laden gas stream. Assuming that fine atomization has been achieved, and the droplets are uniformly distributed throughout the gas stream, then the controlling parameter in cleaning efficiency and the determining factor in the size of particulate that can be removed, becomes the differential velocity between the droplet and the particulate.

Several mechanisms are commercially available to achieve some degree of the desired results and the most familiar is the venturi scrubber. While there are many variations of the venturi scrubber, the general concept is to accelerate the particle laden gas through a restriction in the ducting where water is injected into the gas stream. The velocity of the gas stream provides the dual function of atomizing the scrubbing fluid and providing a differential velocity between the particulate and the liquid droplets. By utilizing very high power fans to accelerate the gas stream, it is possible to generate a gas velocity at the venturi throat of as much as 500 ft. per second. The pressure drop, and therefore the fan horsepower requirement, is directly proportional to the gas velocity squared, and the liquid to gas ratio (the term L/G used herein is the conventional scrubber terminology of liquid, in gallons, over gas flow, in thousands of standard cubic feet). It is obvious that velocities are possible only at a substantial pressure drop which results in a high level of energy expended.

Alternate Scrubber Methods

Another conventional approach to achieving a velocity differential between scrubbing liquid droplets and particulate matter is a high pressure water jet scrubber. In this type of device the liquid is injected at a high pressure into the slow moving gas stream. A proper nozzle configuration will provide satisfactory atomization of the scrubbing liquid and will also induce a modest draft which assists in drawing the gas through the cleaning device. Power requirements for the fan are either eliminated completely or substantially reduced when compared to the venturi type scrubber. However, referring to Figure 1 we find again that a differential velocity of over 500 feet per second is quite difficult to obtain in this type scrubber. The limiting factors are the practical considerations of pump output pressure and reliability of equipment operating at these pressure levels. In an effort to overcome this limitation several devices have been developed which use high pressure gas or steam to provide the motive force to shear and accelerate the water droplets. A number of patents have been issued on devices of this type and some are in operation with varying degrees of success.

TWO-PHASE JET SCRUBBER

During the past five years our company has worked on the development and application of the type of scrubber which overcomes some of the inherent disadvantages of many scrubbers used for the removal of submicron particulate. We have discovered that a pressurized, heated, liquid when passed through a properly designed nozzle will produce a two-phase mixture of vapor and liquid droplets that is an excellent cleaning medium. The droplets can be accelerated to extremely high velocity as a result of the expansion force created by a portion of the liquid being converted to vapor. The general configuration of this type of scrubber is shown in Figure 2. As with the water jet scrubber, the proper arrangement of components allows a draft to be induced which eliminates or drastically reduces fan power requirements. The two-phase jet scrubber produces water droplet velocities which vary with the temperature of the scrubbing fluid as shown in Figure 3.

It is our experience that jet velocities in the range of 1000 feet per second are quite satisfactory for particulate removal in the size range down to 0.1 microns. When these data are presented, we are frequently asked two questions: (1) Is this a supersonic velocity? (2) What noise level is generated from this type of device? The answer to the first question is yes; the velocity in the region immediately downstream of the nozzle is probably substantially supersonic since there is considerable evidence that sonic velocity in a two-phase mixture may be as low as 350 feet per second. However, we believe that the inertial impaction is the controlling mechanism in cleaning and that the existence, or absence of the shock phenomena associated with supersonic flow is not an advantage in the cleaning effectiveness. Thus, the velocity in feet per second is the controlling parameter rather than the Mach Number, or relationship of velocity to the local speed of sound. The answer to the second question is that the device operates at a very low noise level. The sound frequency and level is similar to that generated by a garden hose nozzle.

With respect to the draft producing capacity of this type of scrubber system, it should be evident that this is a pure momentum transfer mechanism; therefore, the amount of draft is a function of the amount of fluid passed through the nozzle and the degree to which this fluid is accelerated. The velocity is a function of initial water temperature, as shown in the previous figure. The effect of water flow rate on system pressure rise is shown in Figure 4 for water at a temperature of 400°F. It should be emphasized that this is a rise in pressure across the scrubber and should not be confused with the pressure drop which is associated with the venturi type scrubber. In most applications the pressure rise produced by the two-phase jet is sufficient to overcome the pressure drop in other components of a complete system.

APPLICATION OF TWO-PHASE SCRUBBING

The most direct application of the two-phase scrubbing system is in the control of emissions from processes which generate high temperature gas, laden with submicron particulate. Typical examples are the various metallurgical furnaces and processes. Figure 9 shows schematically the general arrangement of components for one type of application where the exhaust gas is at an elevated temperature. If the process off-gas is at a temperature of 800°F or above, an economizer type of heat exchanger may be used to transfer thermal energy from the gas to pressurized hot water which is delivered to the heat exchanger by a pump. Water exiting the heat exchanger is delivered directly to the nozzle in its liquid state.

For most applications the water temperature is approximately 400°F and the water pressure is approximately 350 psi, or high enough to ensure that the fluid remains in the liquid state until it has passed the nozzle throat. A properly dimensioned mixing section must be provided for intimate contact between the accelerated water droplets and the particle laden gas. The final component in the scrubbing system train is a separator which will remove the dirty water droplets and allow the clean gas to be discharged. Water drained from the separator is passed to water treatment equipment which may be used to remove substances scrubbed from the gas and to prepare the scrubbing liquid for recycling.

If the process off-gas is at a temperature level above 1200°F, an additional option becomes available in the selection of components. The economizer type of heat exchanger may still be used to deliver heated water directly to the nozzle, or a steam boiler may be used as an intermediate step in the heating of water. If sufficient energy is contained in the gas it is possible that a quantity of steam may be produced which is greater than the demands of the scrubber. This steam is then available for other possible plant applications. Other elements of the system remain essentially the same with the exception of the addition of a method to transfer thermal energy from steam to water. The choice between the steam boiler and the economizer type of system for the very high temperature gases is dictated by local conditions at the site in question.

A number of industrial processes produce a combustible gas which has sufficient heating value to be used as a fuel. Typical examples are carbide furnaces and basic oxygen furnaces with a sealed hood. For this type of application the process off-gas is cleaned and cooled as quickly as practical to reduce the explosion hazard. The two-phase nozzle, mixing section, and separator are similar in configuration to those used in other types of applications. A portion of the fuel gas is drawn off to supply an externally fired water heater or boiler which generates the heated fluid required for the two-phase jet scrubber.

This general type of arrangement may also be practical in some cases where the fuel must be supplied from a purchased source. It can be shown that the total system operating cost, utilizing purchased fuel as opposed to utilizing purchased electricity for a venturi scrubber system, is approximately equal if the venturi pressure drop is approximately 60 inches of water. For greater venturi pressure drop requirements, the cost of purchased electrical energy is increasingly more expensive when compared to fuel costs to achieve the same cleaning results in a two-phase jet scrubber.

Cleaning Performance

Cleaning performance results have been obtained during the last three years with plant installations operated by customer personnel. The point of equipment operated by customer personnel should be emphasized since there is a substantial difference between our trained technical personnel operating the equipment at peak performance, as opposed to customer personnel operating it as they see fit. As a point of interest, the latest system provided by our company has been in operation for three months, and no Aronetics personnel have been at the plant site. These tests have been conducted on a variety of difficult emissions such as solid particulate emitted from submerged arc furnaces. Particle size distributions obtained from this type of photograph are shown in Table I. The large percentage of particles less than 0.1 microns should be particularly noted. The cleaning performance results are shown in terms of outlet grain loading in Table II. These results meet or exceed current projected requirements regarding solid particulate emissions. It should also be noted that opacity requirements are met in all cases with these levels of outlet grain loading.

FIELD EXPERIENCE

It would be a fortunate experience indeed if new equipment were placed in the field without operational difficulties of some kind. The engineering prototype of the two-phase jet system did encounter certain difficulties which required modifications to the original installation. It is perhaps of some value to document the problems encountered and the solutions that were implemented.

The original selection of a heat exchanger, on first cost economic considerations, was a fire tube heat exchanger arranged in a vertical orientation with hot gas entering at the top and hot water exiting from the top of the heat exchanger. While this heat exchanger operated for a sufficient period of time to establish the suitability of the scrubber system concept, it was replaced after a few months of operation because of recurring mechanical and thermodynamic problems. The replacement heat exchanger is of the conventional water tube design utilizing bare tubes arranged perpendicular to the gas flow path. While this type of unit is somewhat more expensive than the fire tube design, it is much more satisfactory.

When the operation of our original engineering prototype was begun, we were astounded to discover that the gas weight flow through the system was 50% less than the value used in the equipment design. While this would have been a favorable outcome for many emission control systems it is not an acceptable situation for the two-phase jet system since it is operated by thermal energy, and the thermal energy available is a direct function of the gas weight flow as well as the gas temperature. In carefully evaluating the design criteria we believe that it was clearly established that there is a fundamental error involved in the measurement of a hot gas flow by the pitotstatic probe method. Results obtained with this method of data acquisition apparently have a consistent bias which indicates a higher gas flow than actually exists.

Other experimenters apparently have encountered this same phenomena; however, we are not aware of a satisfactory explanation at this time. As a result, we have abandoned this method of determining gas flow and use other information which is normally available or can be calculated from the process data. A final and accurate determination of the gas weight flow can be made using a thermal balance method after the installation is completed.

It did not take many days of operation with the original engineering prototype to discover that this equipment would be subject to the characteristic deposition at the wet-dry interface that is encountered in many other scrubber systems. The solution to this problem is the same as that proven satisfactory in other installations. Namely, proper irrigation of the wall at the wet-dry interface.

While the original equipment was designed for particulate removal, it was quickly discovered that the scrubber was quite capable of removing certain gaseous components such as HCL and SO_2. The resulting slurry, naturally, has a very low pH and will quickly destroy separators constructed of unsuitable material. After replacing one set of separators we have become quite conscious of the necessity to identify all components of the emission in order to avoid unnecessary surprises.

Finally, as a result of operating experience we learned that it was necessary to face the water quality problem in conjunction with the air quality problem. With properly designed, and operated, equipment it has been shown to be entirely practical to treat scrubber slurry to the extent that it can be either reused or discharged in the public waterways in a condition satisfactory to meet the recently published Environmental Protection Agency effluent guidelines. It is our opinion that wet scrubber manufacturers will be required in the future to provide their customers with adequate service in the water treatment aspects of the entire pollution control problem.

Along with the unpleasant surprises encountered in initial field experience with new equipment, one would hope to encounter some things that exceed the initial expectations. The most important objective of the entire effort was to satisfactorily remove submicron solid particulate from a gas stream. This aspect of the equipment performance exceeded our expectations as indicated in the summary presented in Table II. As previously mentioned in this paper the soundlessness of the equipment in operation was a very pleasant surprise. No erosion of any kind has been experienced in the Aronetics equipment operating at this time.

One of the important initial objectives of the system, in addition to satisfactory cleaning performance, was to operate at a substantially lower cost for power than other systems with a comparable cleaning performance. Personnel of the Chromium Mining and Smelting Corp. undertook to perform a complete power consumption cost analysis for the two-phase jet system, as installed at their Memphis plant, compared to other types of equipment installed at other plants. We are indebted to Chromium Mining and Smelting Corp. for providing the data presented in Table III.

It is our understanding that all power costs associated with operation of the two-phase jet system was charged to this system. This means that the cost shown covers all water transfer pumps, slurry pumps, air compressors, mixers or other devices which consume electrical energy. The actual power costs were divided by the furnace input power to establish the air pollution control power cost per megawatt of furnace power on an annual basis. In each case this number was multiplied by 40 to adjust each plant to the size of the Memphis installation. As noted in the right hand column the closest competing system had an annual power cost of $152,000 in excess of costs incurred with the two-phase jet system.

The amount of water required for a scrubber system is also a finite operating cost. However, the cost of water varies so dramatically from one location to another that it is difficult to assign a dollar value to the water rate. However, a general trend can be indicated in the L/G ratio to achieve 99% cleaning efficiency with various particle sizes. The trend of these data is shown in Figure 6. It should be kept in mind that the normal venturi L/G is in the range of 10-15 gallons of water per 1000 cubic feet of gas. It is clear that the smaller particle sizes and higher cleaning efficiencies require larger quantities of water.

CONCLUSIONS

Certain types of wet scrubber systems have demonstrated satisfactory cleaning performance in the submicron particle size range. It is believed that inertial impaction is the principal cleaning mechanism in scrubbers of this type. Because of the high energy demands required to operate these scrubbers it is important to consider alternate methods to achieve the desired results. A suitable alternate, the two-phase jet scrubber, has been developed. This system utilizes waste thermal energy to produce a two-phase flow capable of simultaneous cleaning and draft induction. Test results show excellent cleaning performance with particulate as small as 0.10 micron.

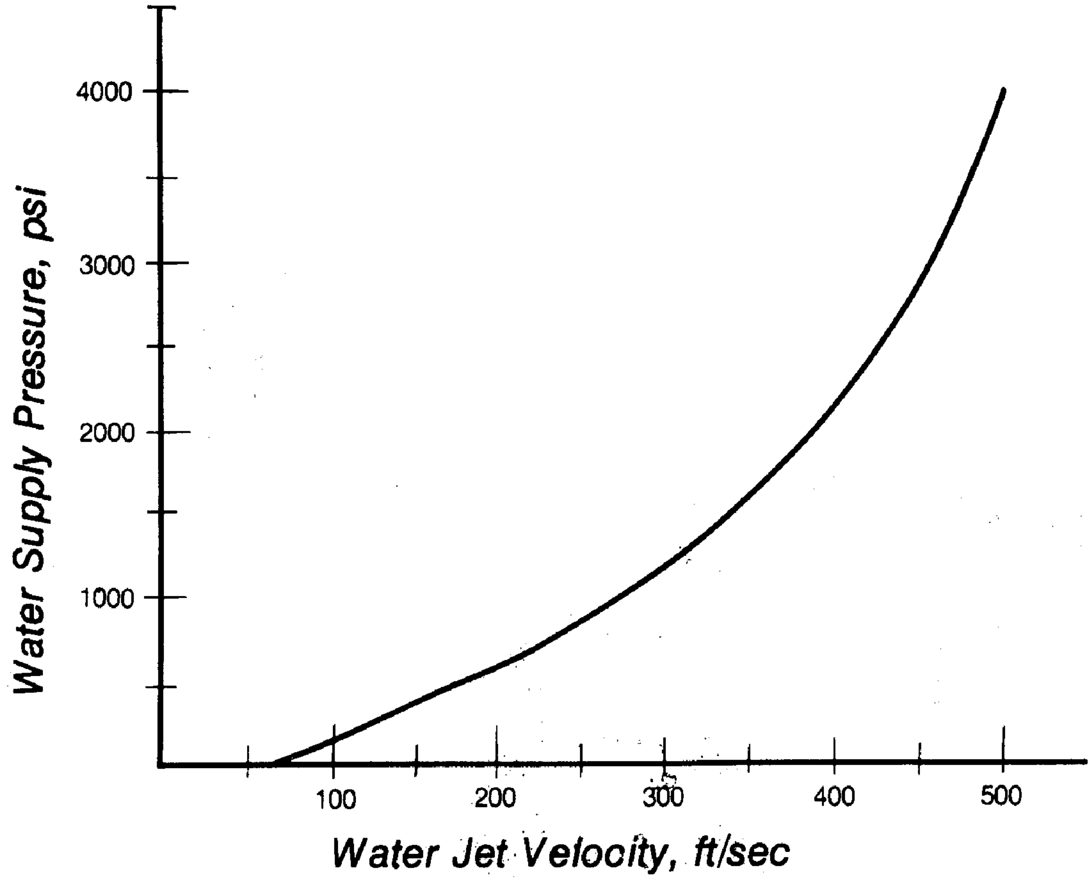

FIGURE 1. EFFECT OF WATER PRESSURE ON WATER JET VELOCITY FOR A TYPICAL JET SCRUBBER

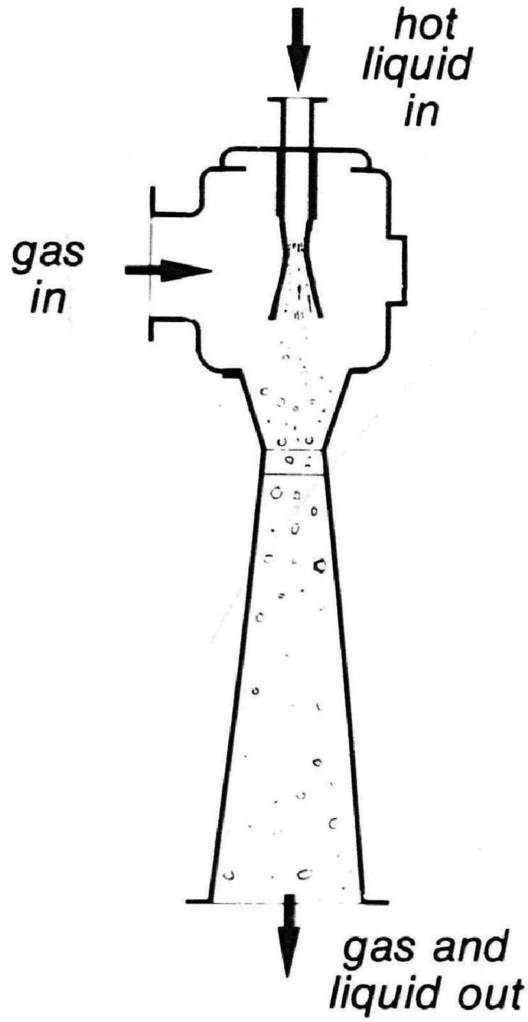

FIGURE 2. GENERALIZED TWO-PHASE JET
SCRUBBER SCHEMATIC

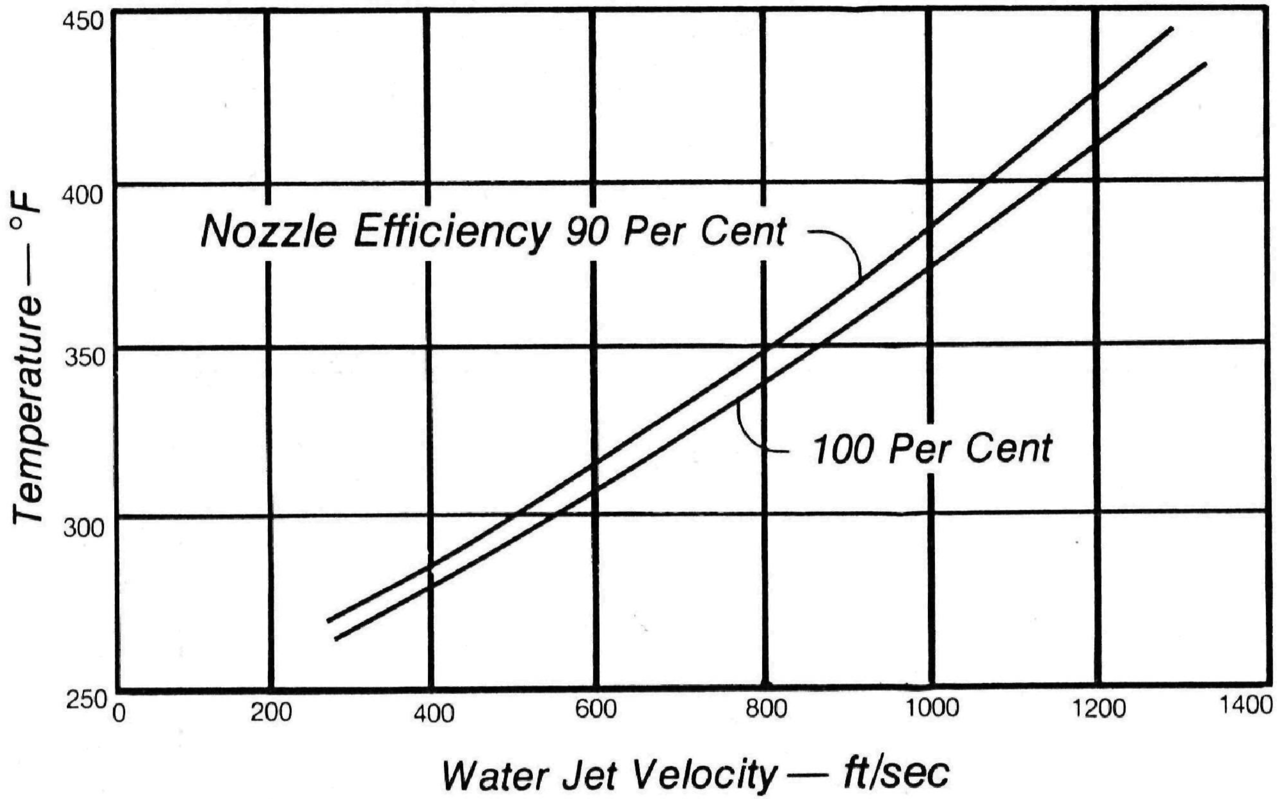

FIGURE 3. EFFECT OF WATER TEMPERATURE ON JET VELOCITY

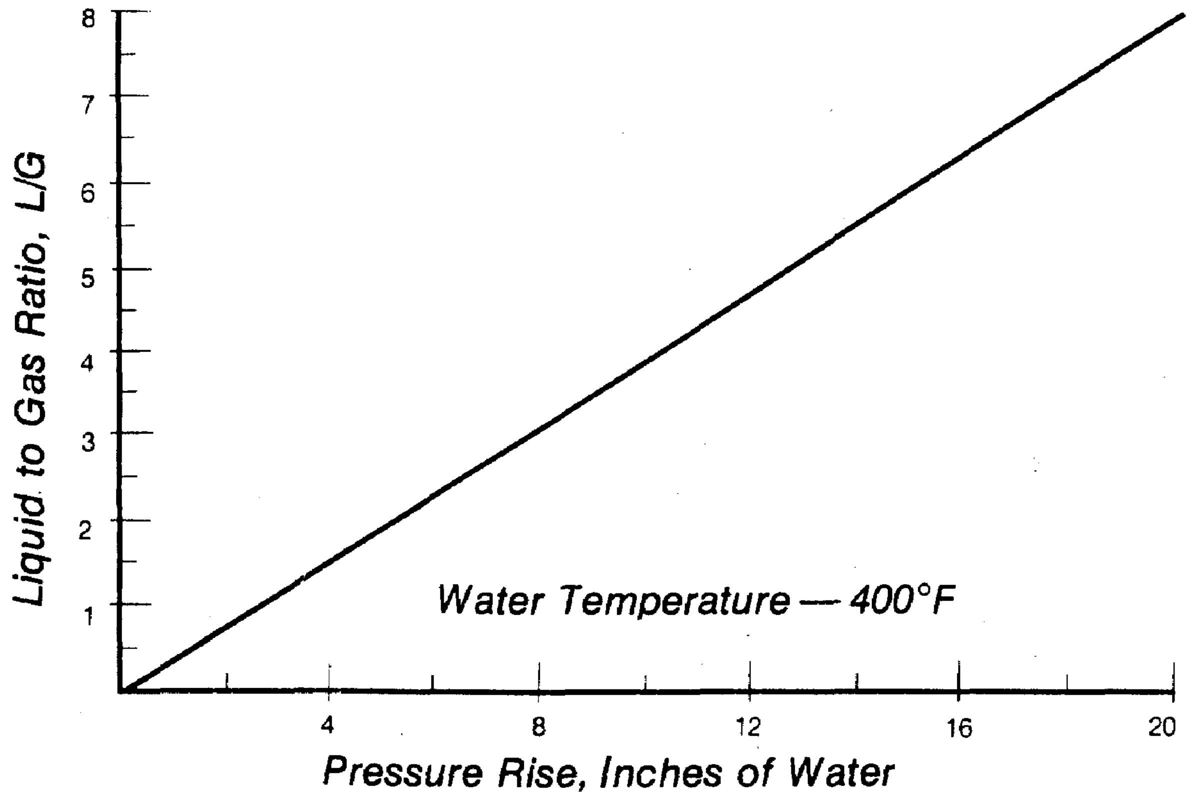

FIGURE 4. EFFECT OF LIQUID TO GAS RATIO ON SYSTEM PRESSURE RISE

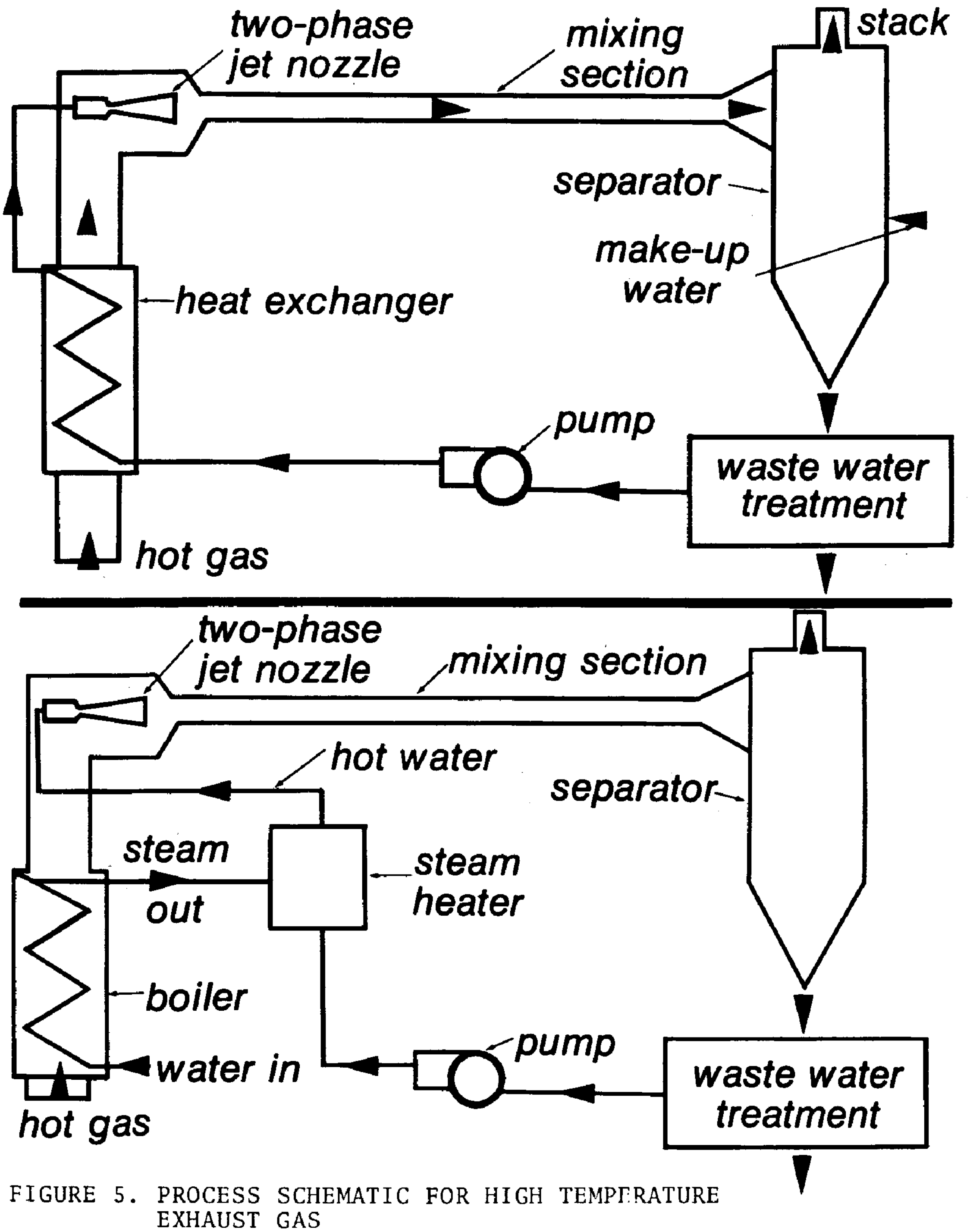

FIGURE 5. PROCESS SCHEMATIC FOR HIGH TEMPFRATURE EXHAUST GAS

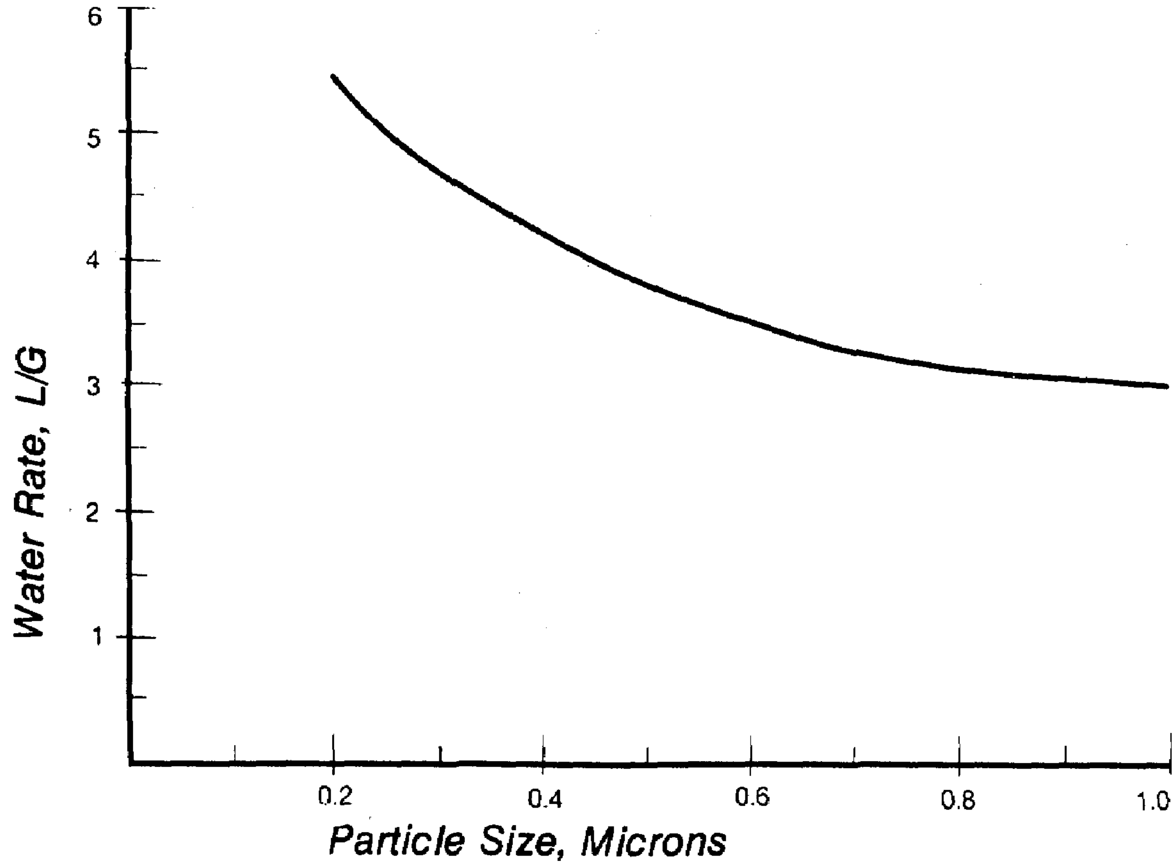

FIGURE 6. APPROXIMATE WATER RATE REQUIRED FOR 99% CLEANING EFFIENCY FOR THE TWO PHASE JET SYSTEM

PARTICLE SIZE DISTRIBUTION OF FERRO - SILICON DUST		
	80% Ferro-Silicon	50% Ferro-Silicon
Finer Than 0.1 Micron	86.57	89.97
Finer Than 0.2 Micron	91.32	92.47
Finer Than 0.3 Micron	97.57	96.63
Finer Than 0.5 Micron	100.00	100.00

TABLE 1. PARTICLE SIZE DISTRIBUTION FOR EMISSIONS FROM FERRO-SILICON FURNACES

Process	Particle Size Distribution	Outlet Grain Loading, Grains/SCF
Steel Making Basic Oxygen Furnace	*50% Less Than 0.1 Microns* *16% Less Than 0.04 Microns*	*0.015*
80% Ferrosilicon Submerged-Arc Furnace	*100% Less Than 0.5 Microns* *86% Less Than 0.1 Microns*	*0.02*
50% Ferrosilicon Submerged-Arc Furnace	*100% Less Than 0.5 Microns* *90% Less Than 0.1 Microns*	*0.02*
Silico Manganese Submerged-Arc Furnace	*85% Less Than 0.5 Microns* *43% Less Than 0.3 Microns*	*0.007*
Charge Chrome Submerged-Arc Furnace		*0.01*
Cement Making Kiln		*0.008*
Carbon Black Dryer		*0.005*

TABLE 2. TYPICAL CLEANING PERFORMANCE RESULTS

Operating Electrical Power for Ferro-Alloy Air Pollution Control Systems

Type System	Plant Size Megawatts	Pollution Control H.P. per Megawatt	Percent of Furnace Power	Annual Power Cost for Air Pollution Control M.W.	Annual Power Cost for a 40 M.W. Plant	Amount of Power Saving With Aronetics*
Aronetics® System	40 M.W. Plant	14	1.2%	$910	$36,400	
Scrubber	18M.W. Plant	85	6.4%	$5,500	$220,000	$184,000
Scrubber	27 M.W. Furnace	106	7.9%	$6,890	$276,000	$246,000
Scrubber	27 M.W. Furnace	106	7.9%	$6,890	$276.000	$246.000
Scrubber	28 M.W. Furnace	95	7.1%	$6,195	$248,000	$212,000
Bag House	17M.W. Furnace	276	20.6%	$17,940	$717,600	$681,000
Bag House	20 M.W.	90	6.8%	$5,900	$235,000	$199,000
Bag House	19 M.W. Furnace	155	11.5%	$10,000	$400,000	$364,000
Bag House	35M.W.	95	7.1%	$6,195	$248,000	$232,000
Bag House	18 M.W. Furnace	72.5	5.4%	$4,712	$188,400	$152,000
Bag House	20 M.W. Furnace	109	8.1%	$7,085	$283,000	$247,000

Power costs based on rate of $0.01 per kilowatt hour
Data courtesy of Chromium Mining and Smelting Corp.

TABLE 3. POWER COST FOR FERRO-ALLOY CONTROL

PERFORMANCE OF A STEAM-EJECTOR SCRUBBER

by

L. E. Sparks
Control Systems Laboratory

and

J. D. McCain and W. B. Smith
Southern Research Institute

ABSTRACT

The results of fractional and overall mass efficiency tests of a steam-ejector scrubber for controlling particulate emissions from an open hearth furnace under several operating conditions are presented. Particulate mass concentrations were determined by conventional (Method 5) techniques and cascade impactors for sizes from about 0.3 μm to 5 μm. Number concentrations were measured for sizes smaller than about 1 μm using optical and diffusional methods.

The measured efficiencies based on total particulate mass concentrations with the scrubber operating under near optimum conditions ranged from 99.84% to 99.9%. The measured fractional efficiencies ranged from a maximum of 99.99% for particles having diameters of 1 μm to values of 97 and 99.9% for particles having sizes of 0.1 μm, 5 μm, respectively.

"Performance of a Steam-Ejector Scrubber"

by
L. E. Sparks
Control Systems Laboratory
and
J. D. McCain and W. B. Smith
Southern Research Institute

As part of a program to develop technology to control fine particulate emissions from stationary sources, the Control Systems Laboratory of the Environmental Protection Agency (EPA) seeks out and evaluates novel devices to determine their potential for collecting fine particles. Emission tests are conducted on those devices which a preliminary evaluation indicates have significant potential for collecting fine particles. These emission tests are designed to determine both the overall mass efficiency and the efficiency as a function of particle diameter of the device. The results of the emission tests of a steam ejector scrubber are presented in this paper. The results reported herein are based on tests performed by Southern Research Institute for EPA (McCain and Smith, 1974) and do not constitute endorsement or recommendation for use by either EPA or Southern Research Institute.

Description of Open Hearth Facility

At the time tests were conducted four of five open hearth furnaces at this plant were operating continuously 24 hours per day. Each furnace produces three 300 ton batchs of steel per day with the production time scheduled for each of the four furnaces staggered by about two hours for logistical purposes, although the actual timing for any one furnace varied somewhat from this schedule. The operations for any one batch were: (1) charging of the furnace with scrap metal, requiring about four hours, (2) addition of iron directly from a blast furnace, requiring about thirty minutes, (3) the refining phase (oxygen lance), requiring about three hours, and finally (4) furnace tapping and pouring, requiring about thirty minutes. The actual emission rate and size distribution of the particulate are quite variable throughout the cycle. This variability causes some difficulty in both measurement and interpretation of data as is described in the discussion section of this report.

The waste process gases, at temperatures of about 1500°F from the four furnaces, are carried through a series of flues, flow controllers, and ducts to three waste heat boilers, each of which supplies steam to drive seven of the scrubber modules shown in Figure 1. The scrubbers are arranged in a semicircle around the boilers. The gas temperature leaving the boilers is about 530°F. The draft for the entire furnace and scrubber system is provided by the steam ejectors in the scrubber modules. Because three boiler/scrubber systems are used to control the emissions from four furnaces, each system treats the emissions from more than one furnace. The system on which the measurements were made was fed primarily by furnaces 3 and 4 with approximately 67% of the gas handled by the system coming from furnace No. 4. The fact that more than one furnace supplied the system being measured also added to the difficulty in interpreting some of the results and made it impractical to attempt to isolate certain portions of the overall furnace cycle for analysis.

Description of the Scrubber

The scrubber tested was a steam ejector scrubber. A diagram of the scrubber is shown in Figure 1. The atomizer chamber is a prescrubber to remove large particles and cool the gas. Fine particle collection occurs in the mixing tube following injection of both steam and water drops. The drops are removed by cyclone entrainment separators.

Measurement Techniques

A total of four measurement techniques were used during the tests. These were: (1) diffusional techniques using condensation nuclei counters and diffusion batteries for determining concentration and size distribution on a number basis for particles having diameters less than approximately 0.2 μm, (2) optical techniques to determine concentrations and size distribution for particles having diameters between approximately 0.3 μm and 1.5 μm, (3) inertial techniques using cascade impactors for determining concentrations and size distributions on a mass basis for particles having diameters between approximately 0.25 μm and 5 μm, (4) standard mass train measurements for determining total inlet and outlet mass loadings.

The useful concentration ranges of both the optical counter and the condensation nuclei counters are such that extensive dilution of the gas streams being sampled was required. Dilution factors of about 65:1 were used for the outlet measurements and about 500:1 for the inlet measurements. In order to insure that condensation effects were minimal and that the particles were dry as measured, the diluent air was dried and filtered, and diffusional driers were utilized in the lines carrying the diluted samples to the various instruments.

Because of the size and complexity of the optical and diffusional measuring systems, and the fact that only one set of equipment exists for measurements of this type, it was not possible to obtain simultaneous inlet and outlet data with these methods. The system was first installed at the outlet sampling location, the scrubber was tuned, and all the outlet data were obtained. The equipment was then moved to the inlet and the necessary inlet data were obtained.

For the purposes of calculating the efficiency of the scrubber, the assumption was made that the inlet data, as obtained above, were a valid representation of that which would have been obtained during the time the outlet measurements were made. Accuracy in the diffusional measurements was limited by process variations and the efficiencies derived from these data are rather uncertain. However, the trends in the fractional efficiencies derived from the data are probably real and the fractions of the influent material that penetrate the scrubber are probably correct to within a factor of two to three.

The optical data are presented on the basis of equivalent polystyrene latex sizes and the indicated sizes can differ from the true sizes by factors as large as two to three. Data obtained using this method were primarily intended as a means of real time monitoring of process changes and the results of changes in the scrubber operation, but also serve as rough checks on the data obtained with the cascade impactors. The sampling system used for obtaining the optical and diffusional data is illustrated diagrammatically in Figure 2.

Inertial sizing was accomplished using Brink cascade impactors for inlet measurements and Andersen impactors for outlet measurements. Sampling was done at near isokinetic rates. Errors due to deviations from isokinetic sampling should be of little consequence for particles having aerodynamic diameters smaller than 5 μm or physical diameters smaller than 2 μm for and assumed density of 5.2 gm/cm^3. Further, because the sampling was at near isokinetic rates, the calculated collection efficiencies for larger particles are probably reasonably close to the true values. Because of the relatively small duct dimensions as compared to the sizes of the impactors, single point sampling was used in the ducts with the inlet impactors at flue gas temperature (∿515°F). The outlet impactors were heated to about 40° above flue gas temperature to insure that no condensation took place within the impactor. Such condensation might cause operational difficulties or lead to incorrect sizing.

Because of the wide disparity in the inlet and outlet mass loadings (inlet ∿1-2 grains/cf, and outlet ∿0.001 grain/cf) complete simultaneity in the inlet and outlet sampling was not possible. Outlet samples were generally of about 6 hours duration while inlet samples were of about 6 minutes duration. Because of the very low outlet loading and the consequent length of the outlet sampling time, it was found to be impractical to attempt to isolate individual portions of the overall furnace cycle for analysis. Since the inlet sampling could not correspond directly with the outlet sampling, an inlet mass loading history for one complete furnace cycle was synthesized for each size interval covered by the inlet impaction stages. Examples of these synthesized histories are shown in Figure 3.

Results

The tests took place on December 4 through December 11, 1973, with December 4 primarily used for instrumentation setup, checkout, and preliminary measurements. Optimization of the scrubber operating parameters was accomplished on December 5 using the optical and condensation nuclei counters. The results of these tests are given in Table I, which includes the three primary operating variables (cyclone accelerator position, steam pressure at the ejection nozzle inlet, and gas flow rate). Direct comparisons of data between some of the test conditions are not meaningful because of variations in the open hearth process. This is especially true of tests that are separated by periods of more than a few minutes. The optimum conditions appeared to be accelerator position 3, steam pressure 250 lbs and 11,000 scfm flow rate. Other conditions tested were accelerator position 2, 250 lbs steam pressure and 15,000 scfm; and accelerator position 3, 300 lbs steam pressure, and 13,000 scfm.

Diffusional data for efficiencies below 0.3 μm were obtained only under the apparent optimum condition. A brief test using the condensation nuclei and optical techniques with the atomizer water turned off indicated a definite increase in the concentration of submicron particles with the atomizer water off. Insufficient data were obtained to fully quantify the effect. Impactor data were obtained under both optimum and non-optimum operating conditions.

Figure 4 shows typical inlet and outlet size distributions as obtained by optical and diffusional methods during oxygen lance, the most stable process during the heat cycle. Figure 5 shows the fractional efficiencies calculated from these data together with a set of typical results from the impactor measurements. Fractional efficiencies based on the impactor data only are shown in Figure 6. The results of EPA method 5 mass train tests are shown in Table II.

Conclusions

The collection efficiency of the steam-ejector air cleaning system is quite high. As measured using conventional (Method 5) techniques the efficiency was 99.90 and 99.84% for two days of testing. Measured fractional efficiencies were about 90% at 0.01 μm, about 70% at 0.05 μm, 85% at 0.1 μm, 99.9% at 0.5 μm, 99.99% at 1 μm, and 99.6% at 5 μm. The minimum in the fractional efficiency at about 0.05 μm is probably real, but the actual value is somewhat uncertain because of difficulties in making diffusional measurements in the time variable open hearth process. The manufacturer's estimate of the energy requirements for achieving the efficiencies given above are approximately 8250 BTU/1000 SCF to 12,750 BTU/1000 SCF for system back pressures ranging from one to six inches of water.

References

J. D. McCain and W. B. Smith (1974). Report to Environmental Protection Agency NTIS No. PB232-436/AS

Acknowledgements

The work reported herein was conducted under Task No. 11 of EPA Contract 68-02-1308.

TABLE I

Optimization of Scrubber Performance

Time	Particle Acceleration Position	Steam Pressure psig	Gas Flow lbs/min	Particles/cm^3* Dia.≥0.06 µm	Particles/cm^3* Dia.≥0.45 µm	Particles/cm^3* Dia.≥1.0 µm	Particles/cm^3* Dia.≥1.6 µm
1130	2	250	1320	0.72×10^4	2.0×10^3	45	2
1140	2	300	1453	0.69	2.0	14	2
1150	2	350	1526	0.90	2.2	200	11
1225	1	250	1404	0.94	> 2.3	2100	105
1230	1	300	1498	1.51	> 2.3	2400	123
1240	1	350	1581	2.24	> 2.3	2400	248
1255	0	250	1510	0.93	> 2.4	> 2400	588
1300	0	300	1612	1.58	> 2.4	> 2400	235
1310	0	350	1702	1.47	> 2.4	1200	214
1330	2	250	1096	0.78	> 2.2	1.6	11
1340	2	300	1182	0.78	> 2.2	1.9	11
1730	3	350	1163	1.38	1.35	6.7	< 2
1740	3	300	1048	1.1	1.24	< 2	< 2
1750	3	250	916	0.79	1.17	< 2	< 2
1800	2	250	1283	0.85	> 2.1	15	< 2

* Concentration of particles larger than the stated size in the scrubber effluent gas stream.

Table II
Mass Train Results Steam Ejector Scrubber

Date	12/10	12/10	12/10	12/11	12/11
Test No.	1	2	3	1	2
Flow/DSCFM	9110	10476	11036	8849	10940
Grains/DSCF Inlet	0.597	0.255	0.525	0.312	0.921
Grains/DSCF Outlet	0.0003	0.0003	0.0005	0.0007	0.0007
Penetration %	0.050	0.20	0.10	0.22	0.076

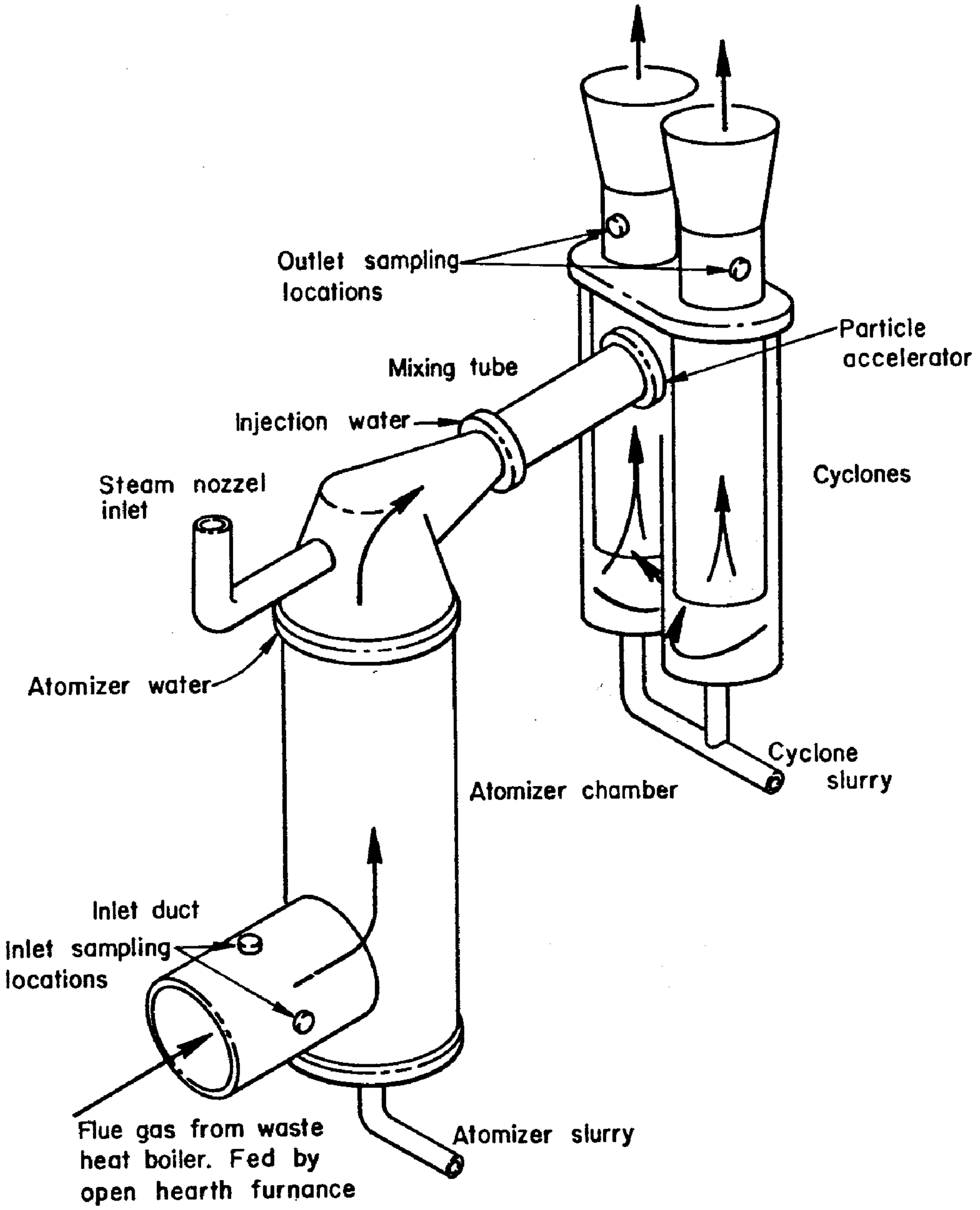

FIGURE 1. THE STEAM EJECTOR SCRUBBER SYSTEM.

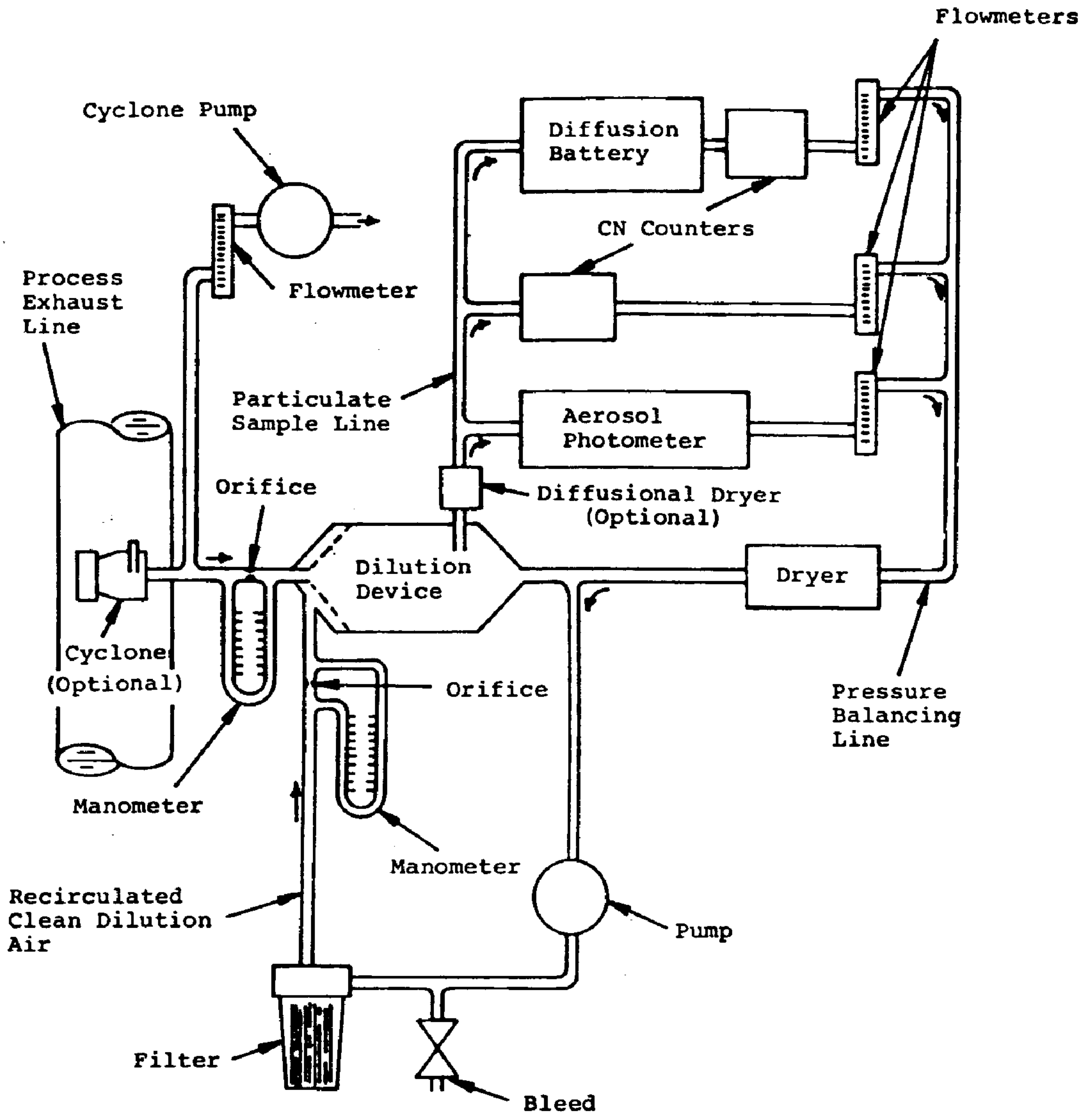

FIGURE 2. OPTICAL AND DIFFUSIONAL SIZING SYSTEM

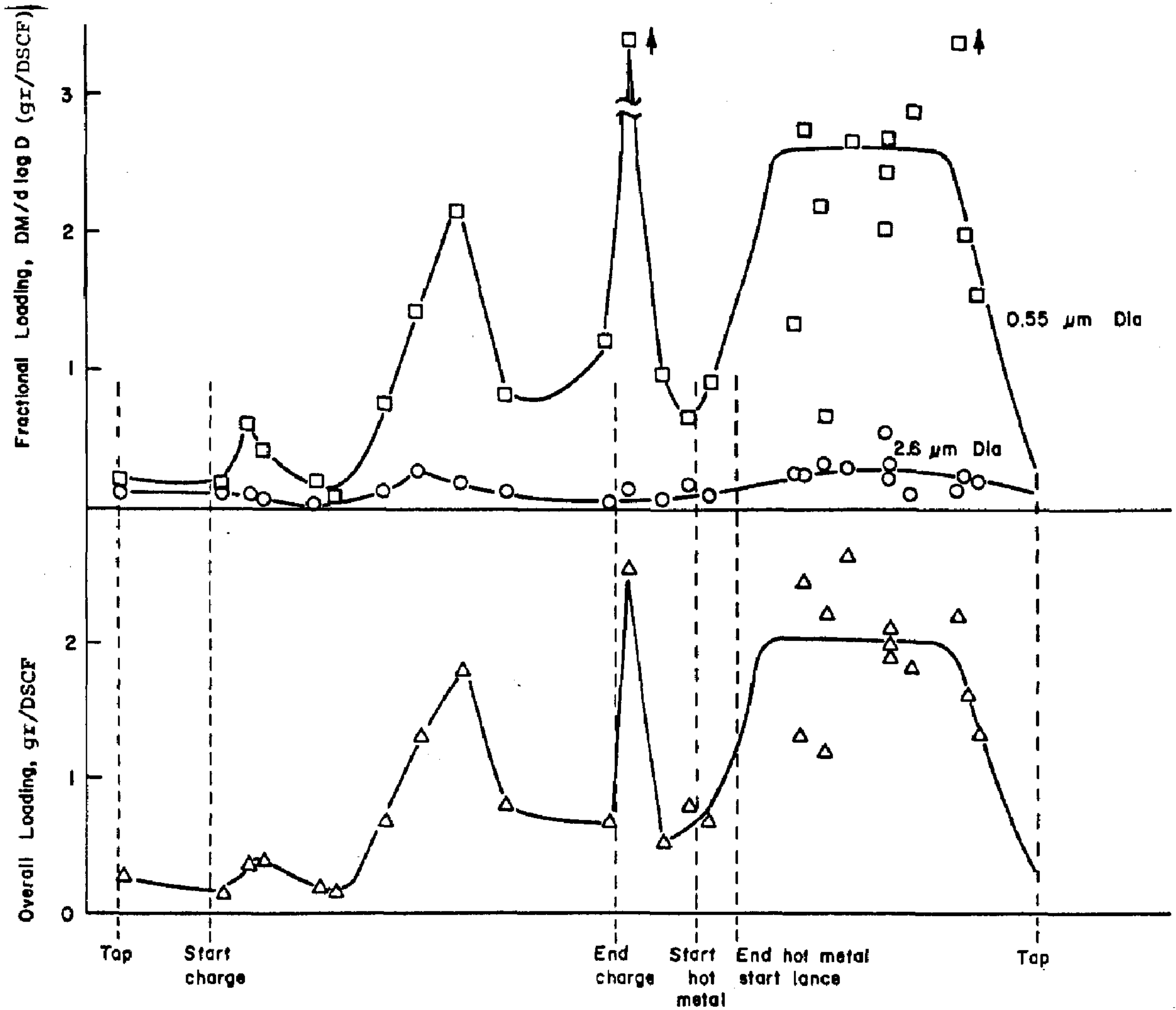

FIGURE 3. TIME HISTORY OF THE PARTICULATE LOADING AT THE INLET OF THE SCRUBBER. THE TIME PERIOD SHOWN IS ABOUT EIGHT HOURS.

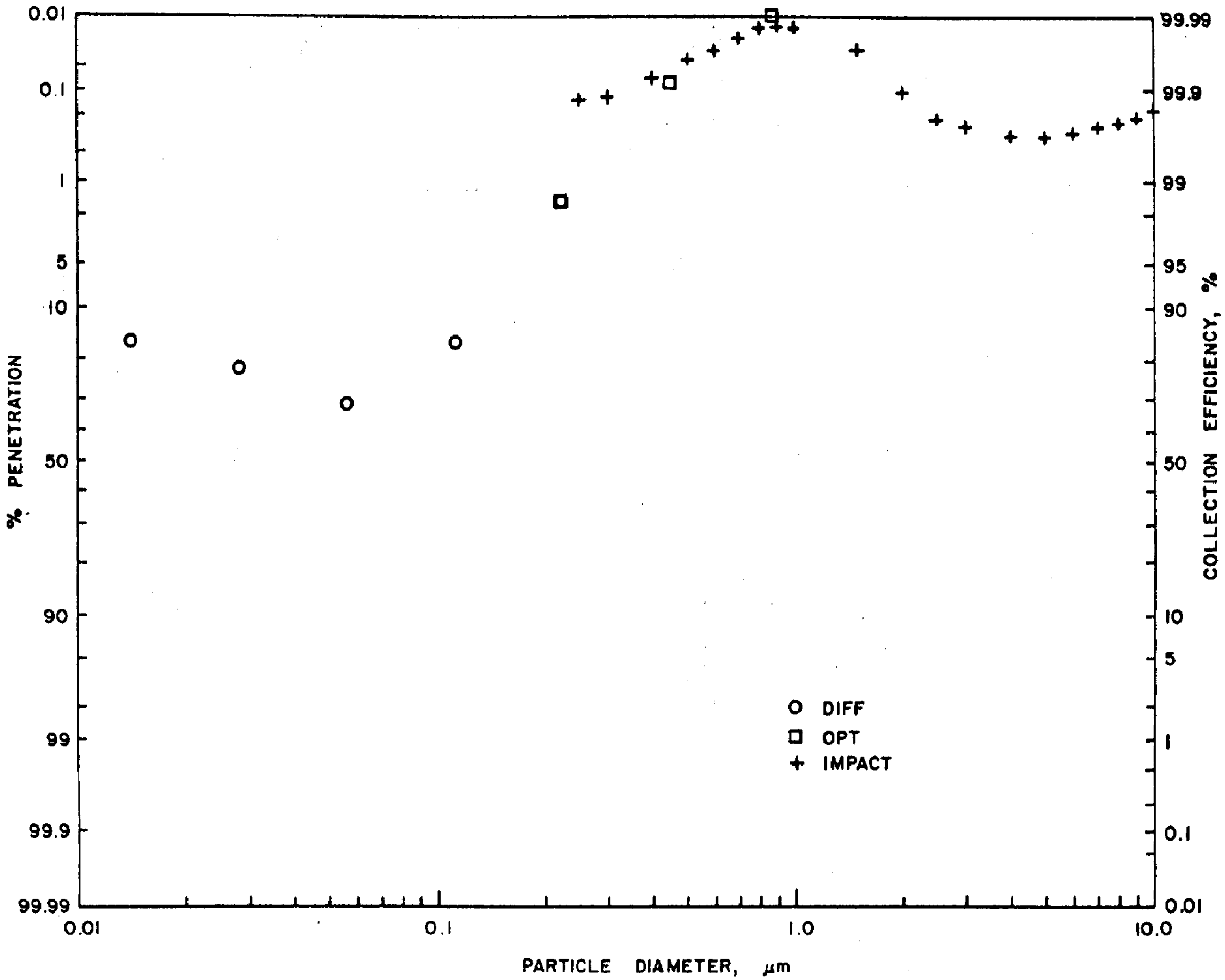

FIGURE 4.FRACTIONAL EFFICIENCY OF THE SCRUBBER

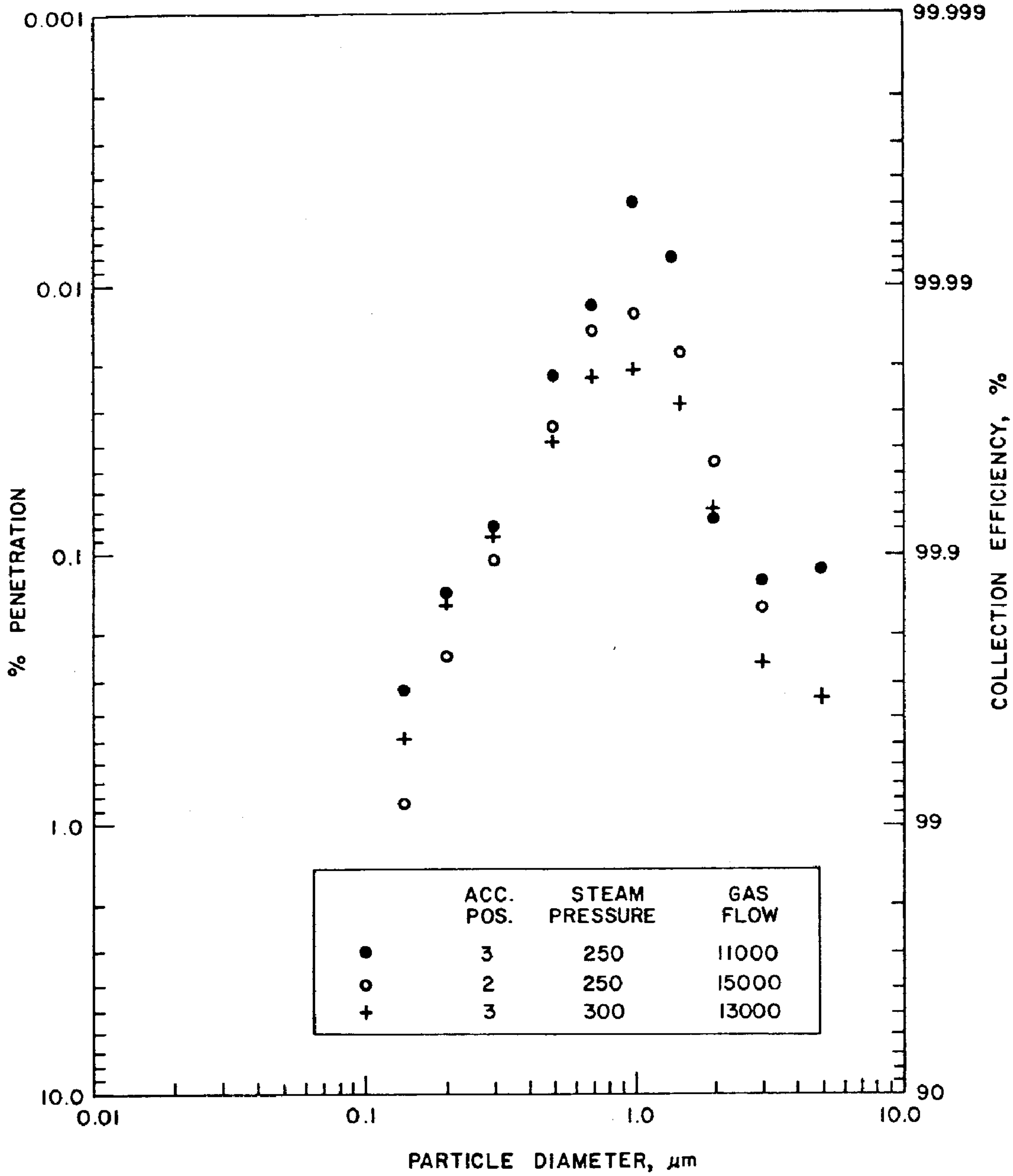

FIGURE 5. FRACTIONAL EFFICIENCY CALCULATED USING IMPACTOR DATA ONLY

PERFORMANCE OF WET SCRUBBERS ON LIQUID AND SOLID PARTICULATE MATTER

by

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Akron, Ohio

ABSTRACT

A general discussion of packed scrubbers for particle collection is presented. Data on liquid entrainment separation, ammonium chloride fume collection, and clay particle collection are given.

Performance of Wet Scrubbers on Liquid and Solid Particulate Matter

by
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Packed wet scrubbers are very good devices for the economical removal of particulates down to a nominal size of 5 μm. Below 5 μm size the removal efficiency of these devices will either begin to fall off or it will be necessary to operate them at higher than normal pressure drops or something over 0.25 in. of water head per foot of packed depth. It is possible to maintain a high efficiency scrubbing action down to about 3 μm particle size, however by this time the pressure drop will be up to 0.75 to 1.0 in. water per foot and severe misting of the irrigation liquid will set in. This is about the upper limit at which a packed wet scrubber can be operated in countercurrent flow. Efficient removal of any smaller particulates will require a different operating technique because this is the limit of loading capability for the countercurrent flow operated packed bed.

Higher gas mass velocities are needed for the removal of smaller size particles which means much more energy will be needed to provide separations. The designer has several choices at this point:

1) Venturi Scrubbing
2) Flooded Bed Scrubbing
3) Fabric Filter Separation
4) Cocurrent Packed Bed Scrubbing

There are possibly others, but the above four are the usual approaches.

Venturis are commonly used, however they are only effective at very high pumping cost for either the gas or the liquid and usually both. Venturis are therefore high consumers of energy though, if properly designed, they should remove particulate matter efficiently down through the 1.0 μm range or less and have been known to be effective on some particulates as small as 0.1 μm.

The flooded bed scrubber is reputed to be as efficient as the venturi with a minimum amount of liquid being required. They are not capable of handling wide gas loading variations and are subject to rather high maintenance costs. Flooded beds are usually operated as multistage devices to achieve good efficiencies. There is a good possibility that a sieve tray or a valve tray would be as efficient as a flooded bed if operated at the same pressure drop per tray as the flooded bed is per bed. They usually end up as operating with about the same overall pressure drop as the venturi and therefore requiring about the same gas pumping energy but with a great saving in liquid requirement, especially if there is some reason for not wanting to recirculate the discharge liquid from the scrubber.

Wet fabric filters are supplied in a wide variety of designs, the most successful of which is probably the Brink. Very good claims are made for this type of separator going down to effective removal efficiency well below 0.1 μm. Various manufacturers claim operating pressure drops from 10 to 40 inches of water. There is one weakness about this type of separator in that it is only good with liquids. The presence of any solids in the gas stream will very quickly blind the filter and require a shutdown of the equipment for either a change of filters or a backwash. Those which operate on the moving belt principle for purposes of cleaning will not effect high submicron removal efficiencies.

The cocurrent packed bed will approximate the venturi in efficiency with the same amount of energy input for the gas.

It has the advantage that it will give increasing efficiency with increasing pressure drop for particles from 3 µm diameter down to 0.1 µm diameter. They do tend to "scale up" somewhat more rapidly than either the venturi or the flooded bed but have a much better operating range than either the venturi or the flooded bed unless the venturi has been provided with a variable area throat to maintain high gas velocity under low loading conditions.

It should be kept in mind that this paper is intended to deal with wet scrubbers so that which has been said above has been on the assumption that all of these various devices will be used to remove particulates from a gas stream when it is necessary to use a liquid as a means of removal or a liquid particulate is being removed. All of this leaves two things in common. First, they depend on wetting the particulate, thus making it a part of the liquid continuum as a means of removing it from the gas stream. Second, they depend on inertial and velocity effects to force a particulate to follow a different path than the gas, thereby achieving an impingement of the particulate on a wetted surface resulting in capture of the particulate by the liquid.

The packed bed will be specifically discussed because it is this type of removal equipment which has received the greatest amount of study by the author from both a laboratory and applications point of view. The application of packings may be divided into two parts, i.e., that of entrainment separation and that of wet washed scrubbers.

Nonirrigated entrainment separators, such as knitted mesh, the Brink entrainment separator, or beds of commercial size packings are all commonly used. If solids are present then some provision must be made to clean the separator after it has become fouled, as will be indicated by breakthrough of entrained material and/or excessive pressure drop. Both mesh type separators and the packed bed are commonly installed with "on stream" backwash provisions but the fabric separator must be used exclusively for the separations of liquids or must be shutdown for cleaning.

Entrainment Separation

The testing of commercial size packings for entrainment separation was done in the laboratory with a conventional 20 in. diameter tower. Pressure drop was measured across the bed as indicated to show when the liquid loading in the bed was approaching flood point. A material balance was taken on the system by measuring the amount of evaporation of water as calculated by the relative humidity of the room air and the exhaust air from the system. Air mass movement was measured by means of an accurately calibrated anemometer. Total weight of water fed to the system was measured and total weight of water drained from the bottom. All measurements were taken at regular intervals until the system had come to a constant operating condition at each rate studied. Efficiency of the entrainment separator was then calculated as follows:

$$\text{Efficiency} = 100 \; \frac{\text{lb/min } H_2O \text{ out the bottom}}{\text{lb/min } H_2O \text{ to fog nozzle} - \text{lb/min } H_2O \text{ evaporated}}$$

The nozzle was a conventional low capacity full cone spray type. At 150 psig on this nozzle, a fog was developed which carried particle sizes ranging from 3 μm to about 50 μm as determined by settling rates in still air. In all likelihood the finer particle sizes represented all of the breakthrough during the highest efficiency performance of the packings.

High removal efficiencies were obtained with velocities as high as 14 ft/sec (Fig. 1) and as the velocity of the air exceeded this figure, the efficiency fell off quite rapidly because the air velocity was sufficiently high to reentrain the smaller droplets of water falling from the wetted surface of the packing. It may be said that the separator is flooded under this condition of operation.

Increasing bed depth (Fig. 2) does not greatly improve efficiency. This is consistent with the findings of Jackson and Calvert (Ref. 1). It is normally not advisable to use beds of less than ten or twelve packing sizes in depth because of the possibility of an occasional unusual void allowing breakthrough. The beds illustrated in Fig. 1 were carefully placed to avoid any unusually large void space, therefore they are applied here at and below recommended safe depths. It is important to keep in mind that gases whose densities are different from that of air will flood at a higher velocity at lesser gas density and lower velocity at higher gas density. Also, the ability of the separator to remove fine particulates at these different gas densities may vary, however this has never been investigated. It is felt though that this effect will be small except at very large changes in density such as gases having densities of the magnitude of less than one-tenth that of air or more than ten times that of air.

Larger packings tend to be less efficient in particulate removal than smaller ones (Fig. 3). The higher capacity packings though can be operated at higher velocities than the lower capacity ones and still maintain high removal efficiency (Fig. 4). The higher capacity packings show a somewhat higher particulate removal efficiency in the same size range than the lower capacity ones.

The removal efficiency of this type of separator appears to be rather good until consideration is given as to just what 2 to 5% breakthrough of particulates represents. Undoubtedly, the entrainment separator, as illustrated by the small improvement with increased bed depth, is acting as a size separator of the particulates, i.e., it is allowing most of the very small droplets to go through.

Depending on their method of generation, solid particulates may or may not be associated with an electric charge. It is because of their departure from sphericity and the tendency to carry an electrical charge that two intriguing problems present themselves. First, what is the particle size of a rod shaped particle 0.1 μm in diameter by 3 μm long or a platelet with an average diameter of 3 μm which is 0.1 μm thick? More interesting yet is that if either of these is electrically charged, how will the charge be distributed? Will it make them behave as spheres? Second, probably because of the shape factor enigma posed above, in most fumes where a solid particulate is present, removal efficiency is only predictable with wet scrubbing by first running an actual test with the material.

Tests were run with a cocurrent (vertical downward flow) packed test tower using a bed of 1 inch plastic Intalox saddles with 3 feet of depth. Ammonium chloride smoke generated in the gas phase was used as the particulate. This smoke based on microscopic examination of material picked up on a Gelman filter paper represents particles ranging in size from less than 0.1 μm to a few as high as 3 μm (Ref. 2). This tower, operating at an overall pressure drop of 7-1/2 in. of water, a water rate of 960 lbs/ft^2-hr and a gas rate of 3300 lbs/ft^2-hr, was capable of removing 60% of the ammonium chloride smoke based on the amount of solids picked up in a Gelman filter at the inlet versus the amount of solids in the filter on the outlet. All samples were taken under isokinetic conditions.

The tower was then tested using a No. 4 dry ball clay. This clay was dispersed into the air stream at a fixed rate.

It was first dispersed with a high pressure air jet and then passed with the air stream through two centrifugal blowers operating in series. All other operating conditions were the same except that the air rate was now increased to 5000 lbs/ft^2-hr.

The clay being insoluble in water made it possible to get an accurate particle size analysis both in and out as well as a distribution count of particle size in both the in and out gases. Particle size count was taken with a Coulter counter (Table I). A removal efficiency of over 80% of particles 1 μm in size was unexpectedly good. From a weight standpoint, the scrubber has removed 98% of the particulate matter in the gas stream which in this case had an average particle size of 0.5 μm.

One acceptable method for the removal of submicron particulates with a wet scrubber is to use a technique known as nucleation. This process (Ref. 3) consists of injecting a condensable gas, usually steam, into the gas stream carrying the submicron particulate in such a manner that the steam will condense. This is usually accomplished by cooling the gas stream with a fog nozzle if it is not already cool enough. As the temperature of the gas falls below the dewpoint, the particles act as nuclei upon which the steam can condense, thereby increasing their effective diameter to such an extent that they can easily be scrubbed out of the inert gas stream. The process has one weakness in that a dwell time of at least 3 or 4 seconds is required for sufficient nucleation to take place. This sets a requirement for sufficient volume to exist in the scrubbing system to allow nucleation to take place before the air enters the scrubber.

Fig. 5 which has been given by the courtesy of the Mine Safety Appliance Company shows the origin of various particulates which may be ordinarily encountered in the atmosphere and their usual size ranges. Lines defining five size ranges or zones have been added to the original table to indicate what type of packed wet scrubber may be used in each zone.

Zone A covers particulates from 75 μm on up in size which may most economically be scrubbed with efficient removal using a cross flow packed bed. If a little soluble gas is accompanying the particulate or if there is a large amount of solid matter present, then the regular cross flow scrubber can be made a bit more sophisticated by converting it to a horizontal cocurrent flow device.

Countercurrent flow will be found to be effective in Zone B or for handling particulate matter down to a little below 5 μm in diameter (this range may be extended to as low as 2 μm if the particles are very elongated and a bed depth of ten feet or more may be used).

It is advisable to use a cocurrent flow for particulates in Zone C or down to 0.5 μm in size. Cocurrent flow is also advisable for larger particle sizes where there is a very heavy loading of solids in the gas stream in that they tend to foul much less than countercurrent or cross flow scrubbers. The operating range of the cocurrent flow scrubber can sometimes be extended to handle particles as small as 0.1 μm by going to bed depths of as much as 6 or 8 feet if the particles are of the elongated type.

Zone D is ordinarily not considered a good region in which to operate packed wet scrubbers if removal efficiencies in excess of 50% are expected. Nucleation techniques must be used in this region to move it to Zone C if wet scrubbing techniques are to be used.

Zone E is where the packed wet scrubber really comes into its very best field of application in that removal efficiencies of 100% may be realized if necessary. In this region particulates come under the influence of diffusional kinetic energy and behave as true gases. This type of equipment is then designed using the classic techniques for gas absorbers employing mass transfer coefficients and vapor pressure drive.

In summary, it might be said that wet packed scrubbers are very effective in the removal of particulate matter from an air stream in particle sizes up to 0.01 m and then in particle sizes from 0.5 m up to whatever size of particulate can be carried in the gas stream. They are ordinarily operated at a temperature below the boiling point of water and are best applied when the material to be removed is of an odorous, corrosive or moist nature.

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TABLE I

PERFORMANCE CHARACTERISTICS OF COCURRENT SCRUBBER ON CLAY

WITH AVERAGE PARTICLE SIZE OF 0.5μm

	IN		OUT			
Particle Size	Wt. g	** No. Of Particles	*Sample Wt. g	*Actual Wt. g	**No. Of Particles	% Of Particles Removed
10μ & over	.07	2.8×10^{7}	.00	.00	0	100.
5 - 10μ	.03	2.8×10^{7}	.00	.00	0	100.
2 - 5μ	.09	8.4×10^{8}	.03	.0006	5.6×10^{6}	99.3
1 - 2μ	.22	2.6×10^{10}	.14	.0028	3.3×10^{8}	98.7
0.5 - 1μ	.26	2.46×10^{11}	.40	.0080	7.58×10^{9}	97.0
0.25-0.5μ	.18	1.37×10^{12}	.28	.0056	4.31×10^{10}	96.9
0.10-0.25μ	.15	1.12×10^{13}	.15	.0030	2.24×10^{11}	98.0
	1.00			0.02		

* Overall Wt.% Removal Was 98

∴ Wt. Out = (Wt.% OUT)(1.00 - 0.98)

** No. of Particles = [Wt.%/25 = Vol.]/Particle Size^3

1 g Sample Assumed Spg. = 2.5

DE ENTRAINING EFFICIENCY

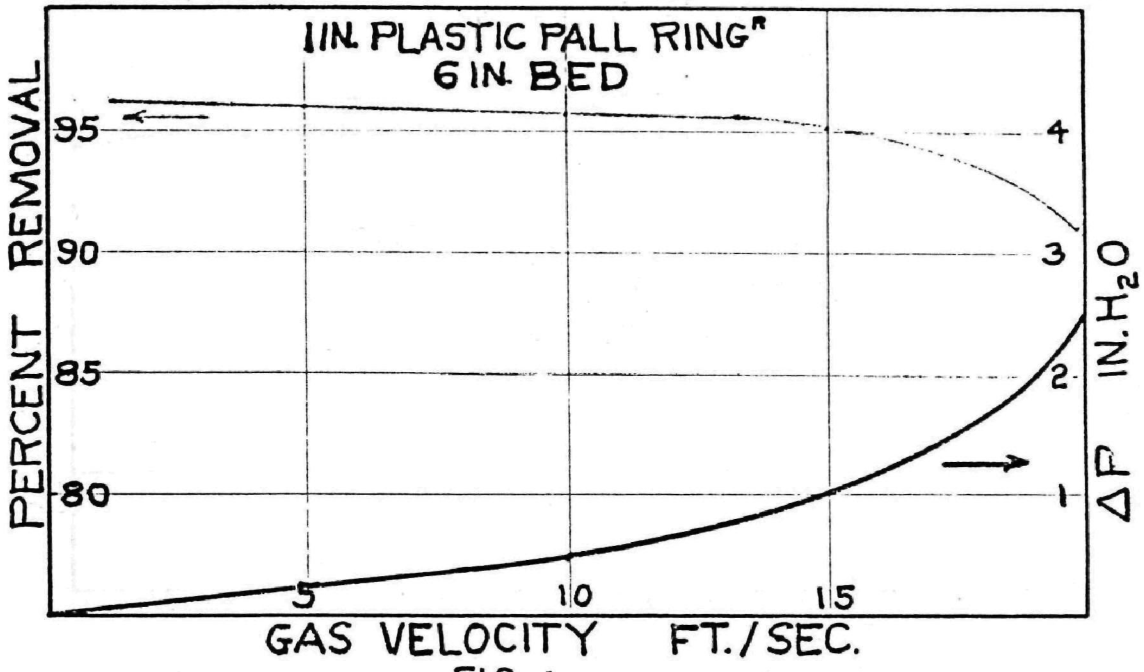

FIG 1

DE ENTRAINING EFFICIENCY

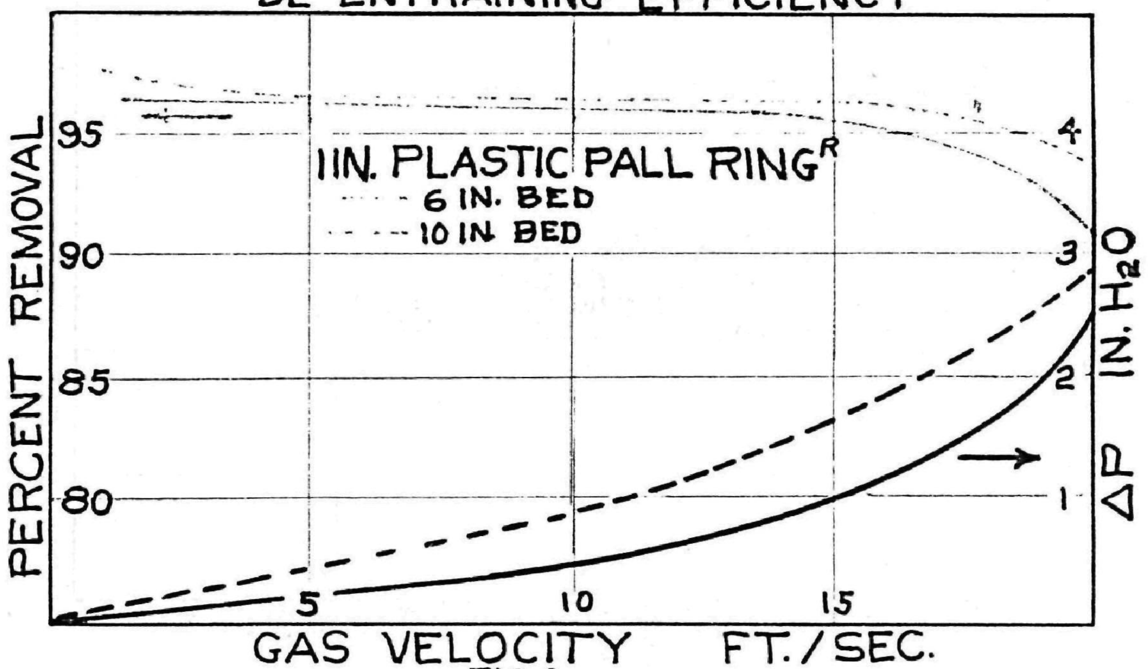

FIG 2

EFFECT OF PACKING SIZE

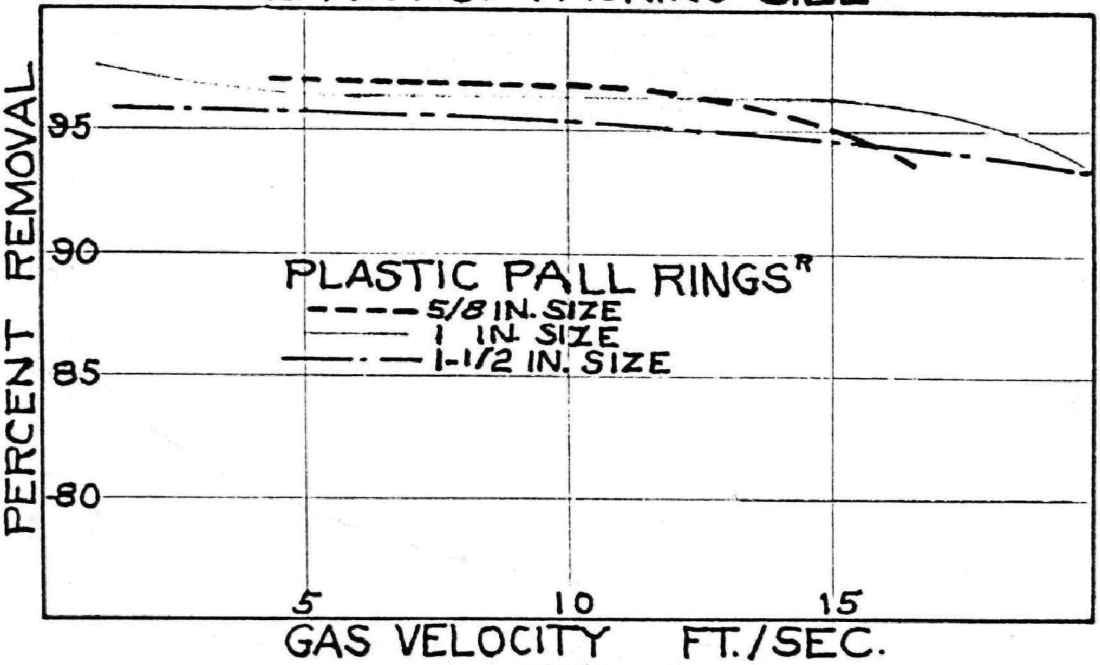

FIG 3

EFFECT OF PACKING TYPE

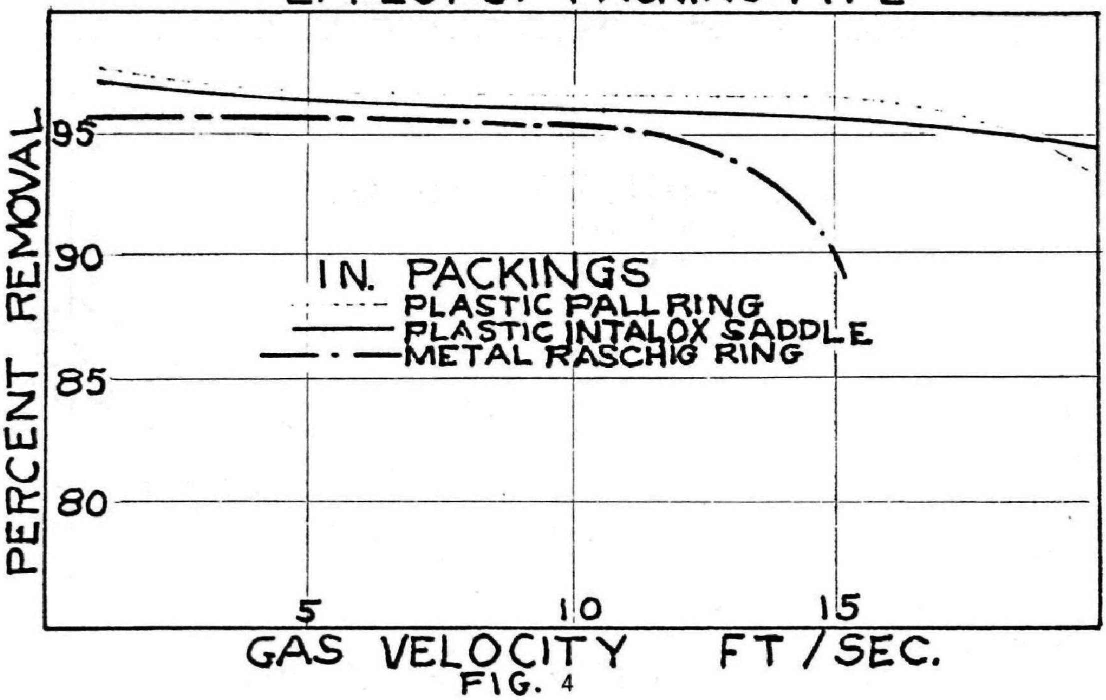

FIG. 4

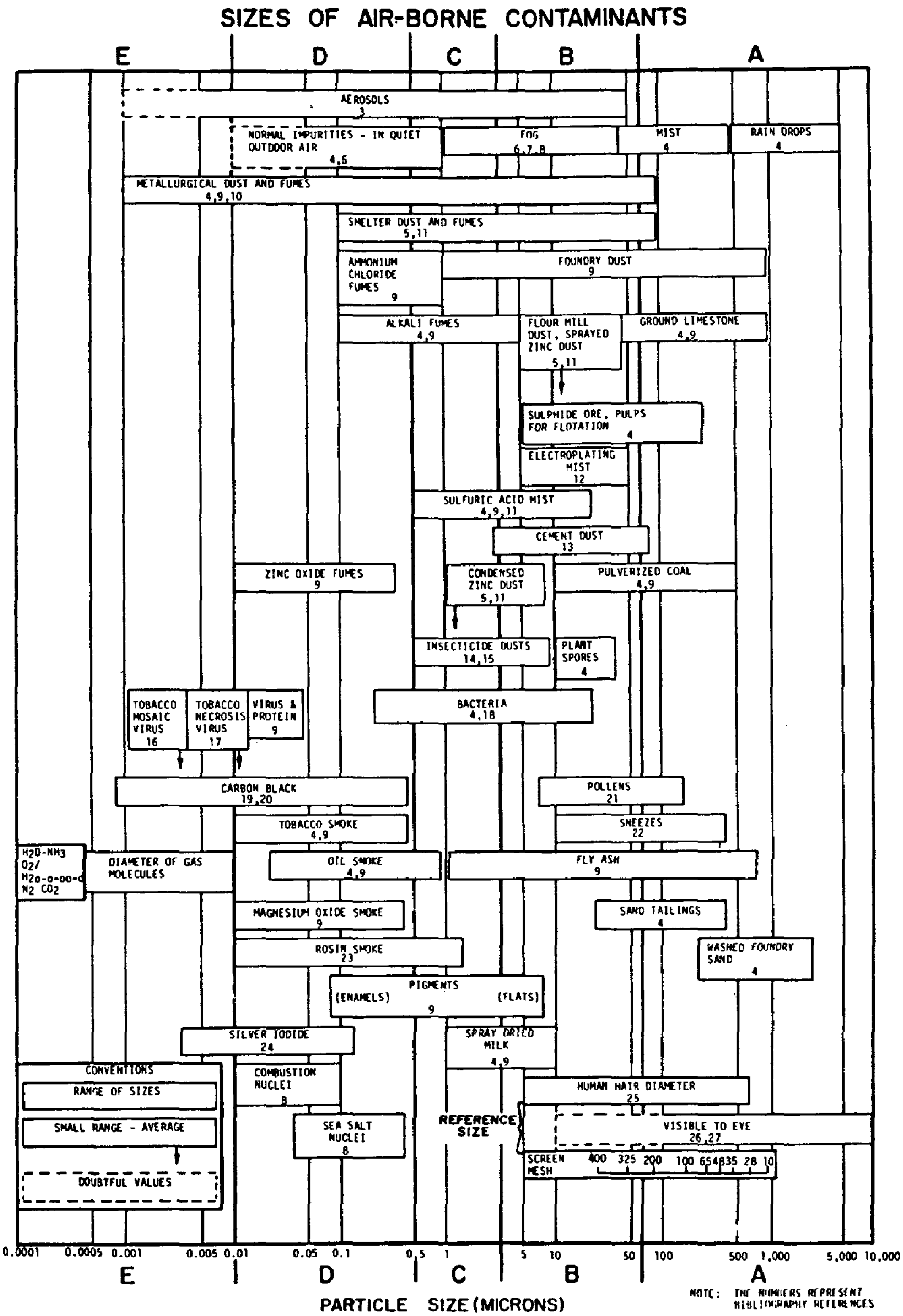
SIZES OF AIR-BORNE CONTAMINANTS
E D C B A
AEROSOLS 3
NORMAL IMPURITIES - IN QUIET OUTDOOR AIR 4,5
FOG 6,7,8
MIST 4
RAIN DROPS 4
METALLURGICAL DUST AND FUMES 4,9,10
SMELTER DUST AND FUMES 5,11
AMMONIUM CHLORIDE FUMES 9
FOUNDRY DUST 9
ALKALI FUMES 4,9
FLOUR MILL DUST, SPRAYED ZINC DUST 5,11
GROUND LIMESTONE 4,9
SULPHIDE ORE, PULPS FOR FLOTATION 4
ELECTROPLATING MIST 12
SULFURIC ACID MIST 4,9,11
CEMENT DUST 13
ZINC OXIDE FUMES 9
CONDENSED ZINC DUST 5,11
PULVERIZED COAL 4,9
INSECTICIDE DUSTS 14,15
PLANT SPORES 4
TOBACCO MOSAIC VIRUS 16
TOBACCO NECROSIS VIRUS 17
VIRUS & PROTEIN 9
BACTERIA 4,18
CARBON BLACK 19,20
POLLENS 21
TOBACCO SMOKE 4,9
SNEEZES 22
H2O-NH3 O2/ H2o-o-oo-o N2 CO2
DIAMETER OF GAS MOLECULES
OIL SMOKE 4,9
FLY ASH 9
MAGNESIUM OXIDE SMOKE 9
SAND TAILINGS 4
ROSIN SMOKE 23
WASHED FOUNDRY SAND 4
PIGMENTS (ENAMELS) (FLATS) 9
SILVER IODIDE 24
SPRAY DRIED MILK 4,9
CONVENTIONS
RANGE OF SIZES
SMALL RANGE - AVERAGE
DOUBTFUL VALUES
COMBUSTION NUCLEI 8
HUMAN HAIR DIAMETER 25
SEA SALT NUCLEI 8
REFERENCE SIZE
VISIBLE TO EYE 26,27
SCREEN MESH 400 325 200 100 65 48 35 28 10
0.0001 0.0005 0.001 0.005 0.01 0.05 0.1 0.5 1 5 10 50 100 500 1,000 5,000 10,000
E D C B A
PARTICLE SIZE (MICRONS)
NOTE: THE NUMBERS REPRESENT BIBLIOGRAPHY REFERENCES

FIG. 5

ROTATING CONCENTRIC HOMOGENEOUS TURBULENCE GAS SCRUBBER

by

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ABSTRACT

A device which utilizes the Couette (secondary) flow patterns, which are developed in a fluid between rotating concentric cylinders, is proposed for use in particle collection. The gas being cleaned is dispersed in the scrubbing liquid within the annular space between cylinders. The device was untested at the time of presentation of the paper.

Rotating Concentric Homogeneous Turbulence Gas Scrubber

by

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Cominco Engineering
Trail, B.C. Canada V1R 4L4

Introduction

A new concept in fine particle scrubbing is presented which utilizes a dirty gas dispersed through an annulus of scrubber liquid constrained between two rotating concentric perforated cylinders, based on the classical theory of couette motion discovered in 1890 (1). Taylor circular couette motion caused by centrifugal forces imposes an adjustable residence time for uniform mixing prior to separation by wetting, absorption, solution, agglomeration and settling of gaseous, liquid, and solid particulates in the annulus of scrubber liquid. Gas scrubbers usually operate with a short residence time, less than 2 seconds, for the dirty gas to impinge and then to penetrate through a fog, mist, spray, jet, or thin liquid curtain of scrubber liquid, whereas this concept permits an adjustable residence time (theoretically) of 5 to 10 seconds for fine particle scrubbing.

Two recent patents (2)(3) in pollution control have demonstrated the practical application of "homogeneous turbulence" with specific regimes of Taylor circular couette motion with a multiple array of single row or double row secondary flow cellular vortices. G. I. Taylor (4) reported the theoretical conditions for the occurrence of multiple arrays of secondary flow cellular vortices in couette motion; and Coles (5) described the specific regimes of Taylor circular couette motion which establish some practical criteria for adjustable residence times.

Gas scrubbers usually operate with a decreased diffusion gradient due to build up of adhering layers of particulates on contact surfaces, whereas this concept should maintain a near-optimum diffusion gradient by an intermittent cleaning cycle.

COMINCO "DOYLE" SCRUBBER

A successful wet impingement scrubber was developed by Cominco as reported by Doyle and Brooks (6), as the final step in certain gas treatment processes to remove essentially all particulate matter from metallurgical and fertilizer plant waste gases prior to their discharge up the stack. The Cominco "Doyle" scrubber depends on impingement of the dirty gas and then penetration through a spray curtain of scrubber liquid, with much success in numerous commercial installations with particulates greater than 5 microns.

However, to meet even today's rigid specifications (with more stringent ones to come), the author suggests that the residence time for the original Cominco Doyle Scrubber, estimated at less than 2 seconds, is too short. Therefore, the addition of "homogeneous turbulence" effects by installation of new hardware in the inlet chamber of a Cominco "Doyle" scrubber, could increase the theoretical residence time to 5 or even 10 seconds - in the author's opinion - which would enhance the fine scrubbing characteristics for particulates less than 5 microns down to 0.1 microns.

Collection Efficiency by Weight

Field tests of collection efficiency by weight related to particle size for a Cominco Doyle scrubber, which uses simple jet impingement effects, can be represented as a straight line on log/log paper, see Figure 1.

Predicted collection efficiency for a rotating concentric "homogeneous turbulence" gas scrubber can be calculated using

Brownian movement where the increased residence time accentuates the increase of Brownian displacement with smaller particle size.

TYPES OF COUETTE MOTION

In general, couette motion refers to motion imparted to a liquid contained in the annulus between two rotating concentric cylinders which move relatively to one another with a uniform angular velocity.

1. Simple Couette Motion, often called shear flow, occurs when the cylinders rotate quite slowly within the ranges of stable laminar flow. There is a linear velocity distribution when the inner cylinder is stationary and the outer cylinder rotates slowly within Rayleigh's theory of laminar stability. When both cylinders rotate slowly in opposite directions, there is a stationary liquid plane at mid-annulus, with a linear velocity distribution in each half-annulus of opposite sign.
2. Taylor Circular Couette Motion includes a multiple array of secondary flow cellular vortices in the annulus between the rotating cylinders with several particular regimes. A single row of helical vortices occurs when the outer cylinder rotates in the same direction and at about half of the angular velocity of the inner cylinder. A double row of helical vortices occurs when the outer cylinder rotates in the opposite direction and about at half of the angular velocity of the inner cylinder. A spiral band of cellular vortices in a travelling wave can sweep upwards or downwards, when the outer cylinder rotates in the opposite direction and about three times the angular velocity of the inner cylinder.

Figure 2 is a sectional elevation of the rotating concentric "homogeneous turbulence" gas scrubber showing the annulus of scrubber liquid between the inner and outer perforated cylinders. Figure 3 shows the multiple array of single row secondary flow cellular vortices when the outer cylinder rotates in the same direction and with about half of the angular velocity as the inner cylinder. Figure 4 shows the multiple array of double row secondary flow cellular vortices when the outer cylinder rotates in the opposite direction and with about half of the angular velocity as the inner cylinder.

Figure 5 shows the specific regimes of Taylor circular couette motion which are relevant to three basic cycles for a pair of gas scrubbers:

CYCLE A

Large (more than 50 microns in diameter) gaseous, liquid, and solid particulates are removed mostly by high velocity impingement of the dirty carrier gas into the scrubber liquid within the inner perforated cylinder with agglomeration, thermal precipitation, and settling of the wetted particulates; and slightly by diffusion gradients (concentration, temperature and mixing) with a short adjustable residence time for uniform mixing prior to separation by wetting, absorption, solution, agglomeration, and settling of the gaseous, liquid, and solid particulates in the multiple array of single row secondary flow cellular vortices in the annulus of scrubber liquid between the inner and the outer perforated cylinders; when the outer cylinder rotates in the same direction and with about half of the angular velocity as the inner cylinder.

CYCLE B

Small (under 5 microns in diameter) gaseous, liquid and solid particulates are removed slightly by impingement of the dirty carrier gas into the scrubber liquid within the inner perforated cylinder with agglomeration, thermal precipitation, and settling of the wetted particulates; and mostly by diffusion gradients (concentration, temperature, and mixing) with a longer adjustable residence time for uniform mixing prior to separation by wetting, absorption, solution, agglomeration, and settling of the gaseous, liquid, and solid particulates in the multiple array of double row secondary flow cellular vortices in the annulus of scrubber liquid between the inner and outer perforated cylinders; when the outer cylinder rotates in the opposite direction and with about half of the angular velocity as the inner cylinder.

CYCLE C

An intermittent cleaning action removes the adhering layers of gaseous, liquid, and solid particulates on the inner and outer perforated cylinders, in a downward direction into the bottom sludge, by a spiral band of turbulence in a travelling wave in the annulus of scrubber liquid between the inner and outer perforated cylinders; when the outer cylinder rotates in the opposite direction and with about three times the angular velocity of the inner cylinder.

CONCLUSION

The rotating concentric "homogeneous turbulence" gas scrubber is an improvement for fine particle scrubbing, which utilizes Taylor circular couette motion caused be centrifugal forces, to impose an adjustable residence time for uniform mixing prior to separation by scrubbing.

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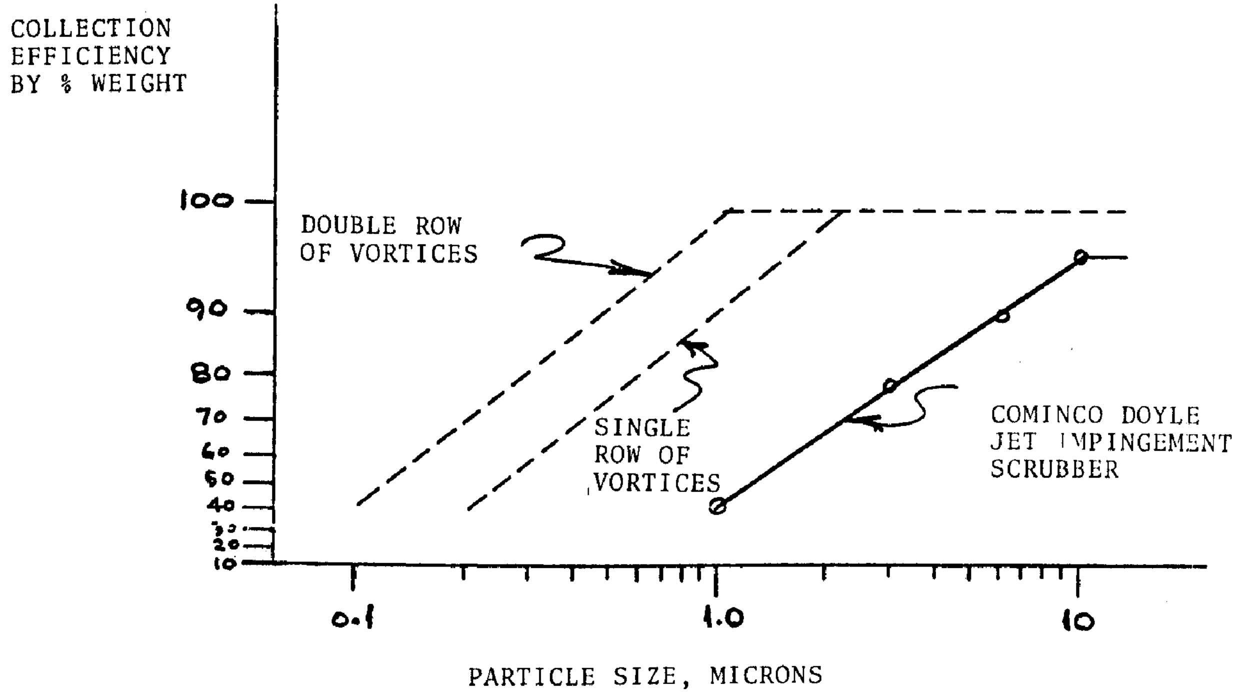

FIGURE 1
PREDICTED COLLECTION EFFICIENCY
FOR A ROTATING CONCENTRIC " HOMOGENEOUS
TURBULANCE" GAS SCRUBBER

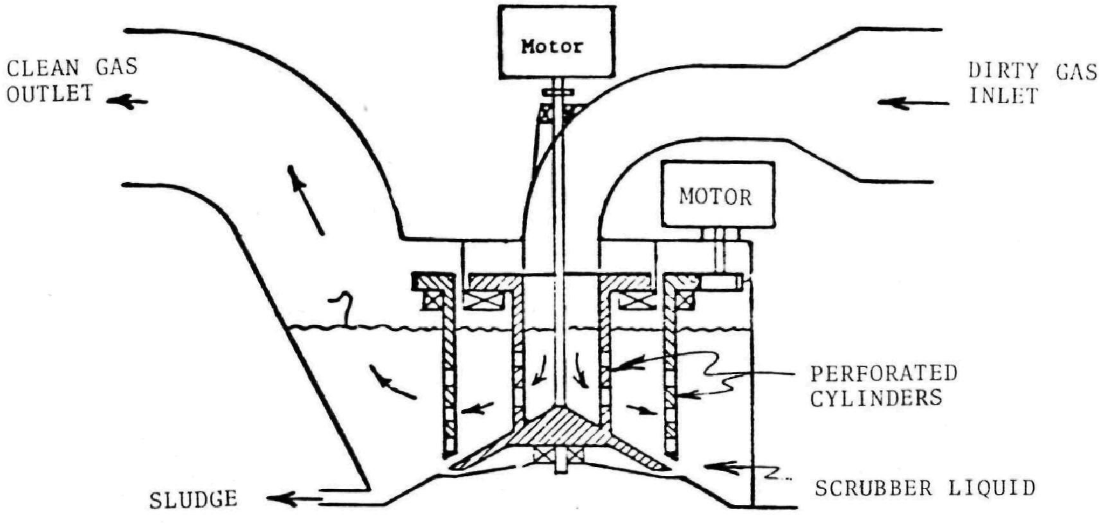

FIGURE 2
ROTATING CONCENTRIC " HOMOGENEOUS TURBULANCE"
GAS SCRUBBER

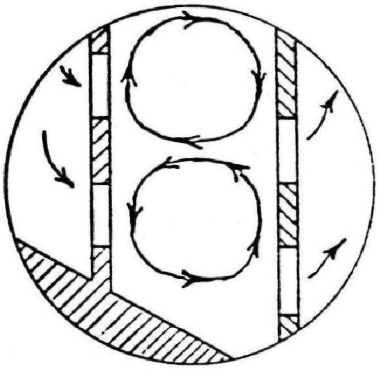

FIGURE 3
SINGLE ROW OF VORTICES

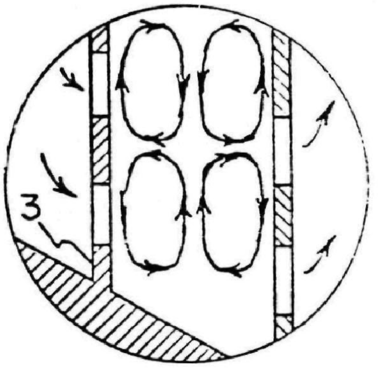

FIGURE 4
DOUBLE ROW OF VORTICES

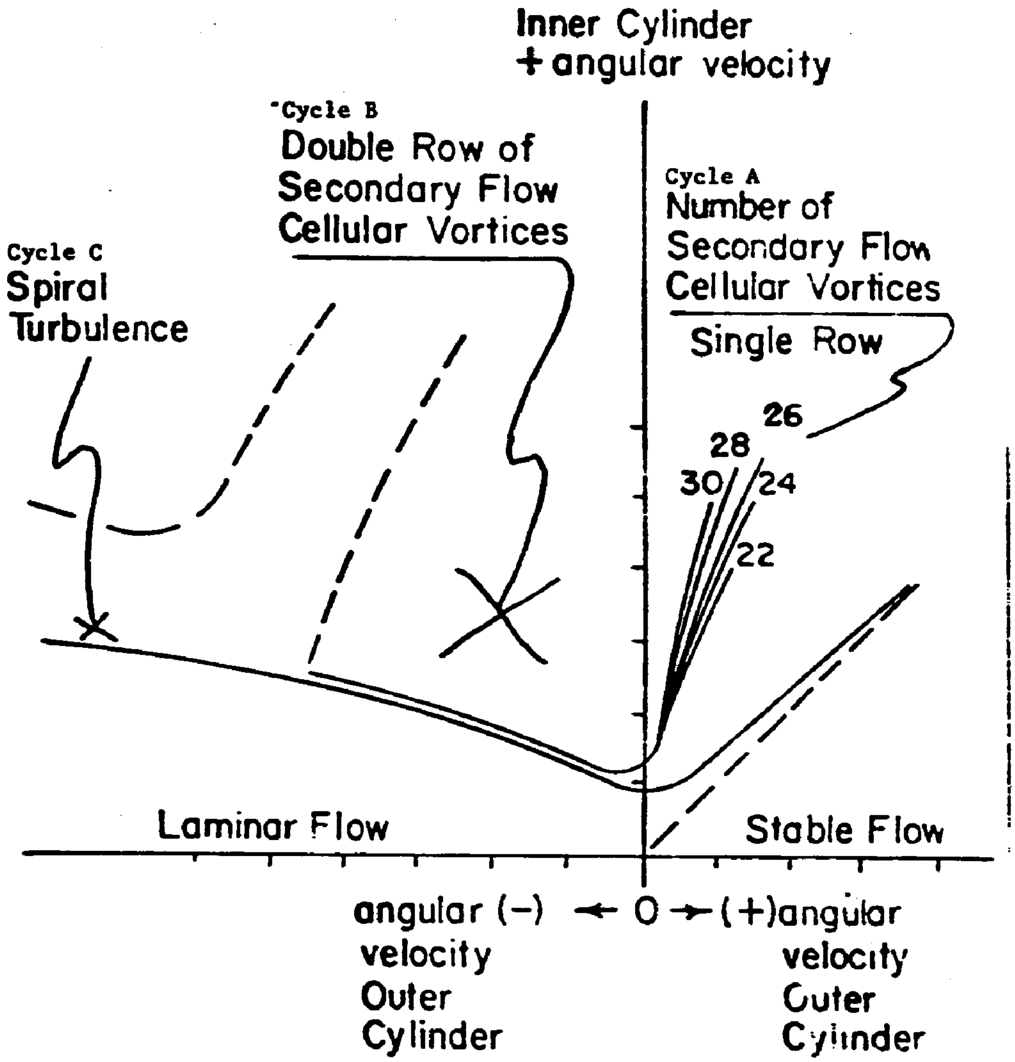

FIGURE 5
SPECIFIC REGIMES OF TAYLOR CIRCULAR COUETTE MOTION

MEAN DROP SIZE IN A FULL SCALE VENTURI SCRUBBER VIA TRANSMISSOMETER

by

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ABSTRACT

This paper describes the construction of and the data obtained from a light transmissometer capable of making mean drop size measurements within about ± 15%. The experimental venturi had a throat flow cross-section of 12 inches by 14 inches and overall length in the flow direction was 15 feet. It was found that the Nukiyama-Tanasawa equation gave accurate estimates of Sauter mean drop size only for a throat velocity of 150 ft/sec.

"Mean Drop Size in a Full Scale
Venturi Scrubber via Transmissometer"

by

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Venturi scrubbers are well known for the ability to collect very small particles. Their main practical advantages are low first cost and minimal maintenance. Their main disadvantage is relatively high pressure drop. Their performance theory, upon which optimized designs can be based, has been developed by several workers[1, 2, 3]. However, the theory invariably starts from presumed knowledge of mean drop size, which is an important basic variable. Moreover, predictions of mean drop size usually invoke the empirical Nukiyama-Tanasawa correlation[4, 5]. Unfortunately, compared with commercial venturi scrubber practice, this correlation was developed using gas velocities that were too high, liquor-to-gas ratios that were too low, and equipment scale that was much too small - so, its use represents an extrapolation. More recent drop size studies, which have been reviewed before[1], tend to confirm the N-T equation, but not in a convincing manner over the full ranges of all the variables.

The purpose of the present study was to help fill this gap by measuring mean drop sizes in a commercial-scale venturi using practical ranges of operating conditions. Since there is no standard method for doing this, we first had to develop an adequate tool.

APPARATUS

Those familiar with the problem of characterizing sprays know that it is easy to make a measurement, but very difficult to make an accurate one. In the present test setup, the problem is compounded by the large volume of spray liquid (up to 200 gpm) and the high gas velocities in the region where measurements must be made (up to 300 ft/sec). These circumstances, combined with the expected variations in liquid distribution across the venturi, made some kind of optical technique virtually mandatory. We chose light transmission because both its theory and practice have been adequately developed[6-11].

Transmissometer Theory

The attenuation of a beam of monochromatic light in traversing a suspension of drops is given by[6, 7, 8]:

$$- \ln \frac{I}{I_0} = \frac{\pi \ell}{4} \int_0^\infty R K_t D^2 N dD \qquad (1)$$

where: $K_t = K_t\ (\alpha, m)$ = theoretical extinction coefficient calculated from the Mie theory[12, 13], dimensionless.

$R = R\ (\alpha\theta)$ = receiver coefficient accounting for the fact that practical light receivers accept some scattered light as if it had not been scattered, dimensionless.

D = Drop diameter, cm

$N = N(D)$ = particle-size-distribution function, drops per cm of diameter per cm^3 of suspension.

I/I_o = Transmission ratio, light transmission signal with drops in the light beam divided by light transmission signal with no drops in the light beam, dimensionless.

ℓ = Light path length through the suspension of drops, cm.

$\alpha \triangleq \pi D/\lambda$ = drop-size parameter, dimensionless.

λ = wavelength of light, cm

m = ratio of refractive index of drops to that of surrounding medium, dimensionless

θ = half-angle of cone of acceptance of light receiver, degrees.

Equation (1) has been verified experimentally for the following conditions[6, 7]:

1. Actual divergence angle of light beam less than 1°.
2. Acceptance angle of receiver, θ, less than 1.5°.
3. Diameter of light beam less than the diameter of the receiver.

4. Transmission ratio (I/I_0) greater than about 0.1. Moreover, if the divergence of the light beam is less than about 0.3° and the receiver and light source are reasonably well aligned (say, within 0.3°) then the R function is given by:

$$R = \frac{1 + J_0^2\,(\alpha\theta) + J_1^2\,(\alpha\theta)}{2} \tag{2}$$

where J_0 and J_1 are Bessel functions of zero and first order, respectively[7, 10]. Values of K_t (α, m) are tabulated in a number of places[11, 14, 15]. Thus, if one but observes the restrictions, all of the physical quantities required to apply Equation (1) are readily available - even without empirical calibration.

To apply Equation (1), it is convenient to rearrange it as follows:

$$-\ln \frac{I}{I_0} = \frac{1.5\,\overline{RK}_t\,C_m\,\ell}{\rho_p\,\overline{D}_{32}} \tag{3}$$

$$-\ln \frac{I}{I_0} = \phi\,C_m\,\ell \tag{4}$$

where:

$$\overline{RK}_t \triangleq \frac{\int_0^\infty RK_t ND^2 dD}{\int_0^\infty ND^2 dD} \tag{5}$$

$$\overline{D}_{32} \triangleq \frac{\int_0^\infty ND^3 dD}{\int_0^\infty ND^2 dD} \tag{6}$$

$$C_m \triangleq \rho_p \int_0^\infty \frac{\pi D^3}{6} N dD \tag{7}$$

$$\phi \triangleq \frac{1.5\,\overline{RK}_t}{\rho_p\,\overline{D}_{32}} \tag{8}$$

That is, $\overline{RK}_t$ is a mean value of the actual light extinction coefficient (dimensionless), $\bar{D}_{32}$ is the Sauter mean drop diameter (cm), C_m is the mass concentration of drops in the light beam (gm/cm^3), and ϕ is the specific extinction cross-section of the drops (cm^2/gm). As a practical matter, the value of $\overline{RK}_t$ is given within 10% by:

$$\overline{RK}_t = RK_t\ (\bar{D}_{32}) \qquad (9)$$

provided only that the drop-size distribution function, N, is of reasonable shape[9]. Thus, for given optics and wavelength, ϕ becomes a function of $\bar{D}_{32}$ alone.

Figure 1 shows ϕ as a function of $\bar{D}_{32}$ for water drops in air (m = 1.33), λ = 7000 Å, θ = 0.35°. Thus, using Equation (4) and knowing the light-path length and the liquid concentration, a measurement of the light-transmission ratio, (I/I_0) gives the Sauter mean drop size. We shall discuss how one can know the liquid concentration, C_m, in a venturi a little later.

<u>Optical Construction of Transmissometer</u>

Figure 2 indicates the light-source construction. A strip-filament lamp is used to maximize beam power for a given divergence angle. Achromatic lenses are used so that they do not have to be repositioned upon changing the operating wavelength. The wavelength (actually the mean wavelength) is determined by the interference filter. In measuring drops, we used λ = 7000 Å with a band width (at half intensity points) of ± 300 Å. The two lenses, C, focus an image of the filament upon the pinhole. The latter is placed at the focal point of lens, K, so that its 1.09 mm diameter and the 149 mm focal length fix the half angle of divergence of the beam at 0.21°. The beam diameter is determined by stop, J, to be about 12.7 mm, or 1/2 inch.

So that the light from the collimated beam can be distinguished from scattered ambient light, the beam light is chopped at 400 Hz by a "tuning fork" chopper, F, in Figure 2. Temporal variations in lamp intensity are monitored by photocell, L, which "sees" some of the light that gets through the pinhole via mirrors, I and G. Stop, H, serves to block backscattered light from the drops being illuminated (not shown).

The receiver optics involve a 2.11 mm diameter pinhole placed at the focal point of the 172 mm focal length lens produces a half angle of acceptance of 0.35°. In the present setup, the distance between the collimating lens of the source and the receiver lens is about 47 inches, making the diameter of the light beam at the receiver equal to 21.4 mm, or about 10 mm less than the receiver lens diameter. The optical axes of the source and receiver were lined up by adjusting the receiver pinhole position within the plane perpendicular to the optical axis so as to center the filament image within the receiver pinhole. It is estimated that this alignment was within 0.02°.

The light source and receiver are mounted together on a common light pipe. The latter is 2.3 inches in outside diameter and about 5 feet long, the receiver occupying the last foot on the far end. The light pipe serves to maintain alignment between source and receiver and to define a path length for the light through the droplet cloud in the venturi. This is accomplished by providing a 2.91 inch slot in the center of the light pipe and inserting the light pipe through the venturi transverse to the gas flow.

Transmissometer Electronics

The silicon photocells are Solar Systems Type SS-300-2. These have the characteristic of producing a current that is linearly related to incident radiant power provided that the voltage at the photocell output terminals is maintained close to zero. In the present instance, this is achieved by connecting them to the input terminals of a high-gain operational amplifier, Burr-Brown Model 3104A/12C. The amplifier output is fed back through a resistor, making the amplifier output voltage linearly related to the radiant power falling on the photocell. These operational amplifiers and their associated circuitry are located within the source and receiver housings to minimize pickup and noise.

During "dark" periods, when the chopper vanes in the source are closed, the output signals from the preamplifiers are sampled and proportional dc signals are negatively fed back to the inputs of the Burr-Brown amplifiers so as to effectively cancel the preamplifier outputs. This eliminates spurious contributions to the preamplifier signals from stray light and/or preamplifier imbalance.

During "light" periods, when the chopper vanes are open, the preamplifier output signals are again sampled and converted to corresponding dc signals. The latter are fed to a Philbrick Model SPLRA/N log-ratio amplifier. This amplifier produces an output signal that is linearly related to $(- \ell n\ I/I_0)$. Gain and zero adjust circuitry is provided to convert this into an actual output indication that is equal to $(- \log_{10}\ I/I_0)$.

Power supplies and timing circuits complete the electronics package, which is housed in a portable 18" x 12" x 12" box. The read-out meter linearity was found to be within 0.007 $\log_{10}$ units, an accuracy within about 1.5% of reading.

<u>Proof Tests of Transmissometer</u>

A few measurements were made on plastic beads to check the overall accuracy of the transmissometer's optics, transducers, and electronics. The data of Figure 3 and Table 1 are typical of the results. These were obtained using uniformly sized plastic beads supplied by the Dow Chemical Co.

The data of Figure 3 were obtained by pipetting one-ml portions of a stock solution of beads into a 5 cm x 5 cm x 10 cm high transmission cell initially filled with distilled water. The concentration of the stock solution was measured gravimetrically by evaporating a portion to dryness. It will be noted that the data are very nearly linear (in agreement with Equation (4)) up to about $I/I_0 = 0.1$. Increasing departure from linearity occurs beyond this point, possibly because of slight polychromaticity of the "monochromatic" light, possibly because of the effects of multiple scattering. Thus, linearity of phototubes and electronics is confirmed.

Table 1 is a comparison of experimental and theoretical values of the specific extinction cross sections, ϕ. The theoretical values of K_t were obtained from the tabulations of Chu et al.[14] by plotting K_t versus $(m^2 - 1)\ \alpha/(m^2 + 2)$, which removes most of the effect of relative refractive index, m. It will be noted that the experimental ϕ values are 0.8% above 7.0% below the theoretical values. The probable causes of these slight discrepancies would include:

1. Very slight nonlinearity of the data plots (Figure 3) even below $I/I_0 = 0.1$ (at most 3% of the log I/I_0 reading).
2. Slight inaccuracy of the λ values due to filter tolerances (at most 5%).
3. Slight inaccuracy of the K_t values because of the uniformly sized particles and the use of smoothed plots rather than precise calculation.

In the measurement of drops in a venturi, items 2 and 3 become unimportant because the larger drops have a K_t value that is independent of λ, and the dispersion of sizes tends to average out the minor variations of K_t with the size parameter (α). Thus, for measuring drop sizes, the data imply that the transmissometer is probably accurate within the validity of Equations (4) and (9), i.e., within 10%, assuming C_m and ℓ are precisely known.

Venturi Construction

The flow cross-sectional area of the venturi throat is 12 inches by 14 inches. This gives a total gas flow of about 20,000 cfm at a throat velocity of 300 ft/sec. In a commercial venturi, the 12-inch dimension would become several feet. Thus, the laboratory venturi amounts to a 1-ft slice taken out of a full-scale commercial venturi. The other dimensions of the venturi are shown in Figure 4. The liquor injection nozzles are Spraying Systems "Vee Jet", No. 3/4U80400. The transmissometer can be moved in and out so that the slot in the light pipes samples different transverse positions in the venturi diffuser.

Transmissometer Position in Venturi

Wherever the liquor drops and the gas are traveling together at the same velocity, the liquid concentration (gm/cm^3) must be numerically equal to the ratio of liquid and gas flow rates. If the liquid is going slower than the gas, as it is when it is first injected, then the liquid concentration must be higher than the flow ratio. The converse is true in the lower part of the diffuser, where the drop velocity exceeds the gas velocity. To be able to know the liquid concentration, C_m, in Equation (4), then, it is essential to place the transmissometer at the point in the venturi where the liquid and gas velocities are substantially equal. Fortunately, this position is not too greatly affected by variations in venturi operating conditions and drop size.

To locate the proper transmissometer position, we used the mathematical model previously developed[1] to calculate drop-velocity profiles for wide ranges of liquid-to-gas ratios, throat velocity, and drop size. Results are summarized in Table 2. It can be seen that the point where drop and gas velocities are equal varies from about 4.5 to 61 inches below the throat. However, at a point 24 inches below the throat, the relative velocities generally differ by less than ± 15% for individual drops that are, respectively equal to, half, and twice the N-T size. On the other hand, since actual drop populations contain sizes that are both larger and smaller than the mean, the average error should be less than this extreme - say $\pm$ 10%. Further considering the $\pm$ 10% accuracy of approximating $\overline{RK}_t$, Equation (9), results in an estimated overall accuracy of about $\pm$ 15%.

Procedure

At each set of venturi operating conditions (throat velocity and L/G), transmissometer readings were taken at five positions across the diffuser. At each position, the liquor flow was temporarily cut off by shutting down the recirculating pump. This permitted a transmissometer reading to be obtained with no drops in the light path so as to permit correction for the few drops that invariably got onto the lenses of the light source and receiver. The correction (in log units) was subtracted from the reading with water flow on. The correction was maintained less than 0.3 log units by periodic cleaning the lenses.

The five corrected readings ($- \log I/I_0$) were averaged to obtain the ϕ value according to Equation (4). The value of C_m was taken to be equal to the liquor-to-gas ratio. The value of ℓ was taken to be the slot length, 2.91 inches. The value of $\bar{D}_{32}$ was, then, obtained from the ϕ value via Figure 1.

RESULTS

Mean drop size data from the transmissometer are plotted as solid points in Figure 5. For comparison, the predictions of the Nukiyama-Tanasawa equation are given by the curves terminating in similarly shaped open points. It will be noted that the N-T equation is accurate only for the data at a throat velocity of about 150 ft/sec (109 ft/sec at the point of liquid injection). Otherwise, it underestimates the effect of gas velocity rather seriously, predicting drop sizes about 48% too large at a throat velocity of 300 ft/sec and about 25% too low at a throat velocity of 100 ft/sec.

An empirical equation that correlates the present data fairly well is:

$$\bar{D}_{32} = \frac{283{,}000 + 793\ (L/G)^{1.922}}{v_i^{1.602}} \qquad (10)$$

where: L/G = Liquor-to-gas ratio, gal/1000 ft^3.

v_i = Gas vleocity at the point of liquid injection, ft/sec.

$\bar{D}_{32}$ = Sauther mean drop size, microns.

The predictions of this equation are indicated in Figure 7 by the "star" shaped points. It will be of interest to note that the present gas velocity exponent of -1.602 agrees well with Wetzel and Marshal's[16] exponent of -1.68 obtained from spraying wax in a small venturi. (Further comparison is, however, inappropriate because they included an orifice-diameter effect and omitted L/G).

Figure 6 shows how liquid distribution can be affected by venturi operating conditions. The plotted distribution function is just the local value of $(-\log I/I_0)$ divided by the average value. Thus, assuming $\bar{D}_{32}$ does not vary across the venturi, the distribution function shows how liquid concentration, C_m, varies. It will be noted that, at the higher throat velocity, there is a distinct tendency for injected liquid to fail to penetrate all the way to the venturi center line. Moreover, even at the lower throat velocity, there is a distinct tendency for the point value of liquid concentration to vary by a factor of two or three in traversing the venturi. Indeed, this kind of variation is typical of the thirty runs made in the present series. Thus, even liquid distribution that appears uniform to the eye may contain enough transverse maldistribution to explain theoretical overprediction of particulate collection[1].

CONCLUSION

A transmissometer has been constructed that is well suited to measuring mean drop sizes in full-scale venturi scrubbers. Its accuracy in measuring $\bar{D}_{32}$ is probably within $\pm$ 15%. Its application has shown that the Nukiyama-Tanasawa equation gives values of mean drop size that are accurate within about 50% for L/G's and throat velocities of commercial interest. However, at least in the one venturi geometry so far studied, the N-T equation consistently overestimates mean drop size at high gas velocities and underestimates it at low gas velocities. An empirical equation (Equation (10)) involving gas velocity to the -1.602 power is much more successful. Additional data for other venturi configurations would be highly desirable.

The transmissometer also provides a practical quantitative means for studying liquid distribution in venturis. Indications so far are that this distribution is far less uniform than one might suppose from a visual observation. Indeed, it seems likely that maldistribution is the main reason that theoretical assessment of particle collection typically overestimates actual performance.

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TABLE 1 TYPICAL BEAD TEST RESULTS

λ air, Å	7,000	6,000
Bead Size, Microns	0.714	0.714
ρ_p, gm/cm^3	1.05	1.05
m	1.193	1.193
α air	3.20	3.73
α water	4.25	4.96
$\alpha\theta$, °	1.12	1.30
R	1.00	1.00
K_t	1.23	1.65
$\phi_{theor.}$, cm^2/gm	24,600	33,000
$\phi_{exp.}$, cm^2/gm	24,800	30,700
$\phi_{exp.}/\phi_{theor.}$	1.008	0.930

TABLE 2 RELATIVE LIQUID AND GAS VELOCITIES

Liquid-to Gas Ratio gal/1000 ft^3	Throat Velocity (ft/sec)	Mean Drop Diameter (microns)	Intersection of Gas-Liquid Velocity Curves (in. below bottom of throat)	Liquid Velocity Relative to Gas Velocity at Point 24" Below Throat, %
			Nukiyama-Tanasawa Drop Size	
4.5	100	217	24.27	-1
4.5	200	120	21.83	+5
4.5	300	86	13.19	+6
4.5	400	68	8.78	+7
9.0	100	241	26.59	-1
9.0	200	145	19.74	+2
9.0	300	110	17.60	+4
9.0	400	93	15.37	+4
18	100	311	35.02	-7
18	200	214	28.60	-4
18	300	180	28.51	-3
18	400	162	28.47	-3
			1/2 Nukiyama-Tanasawa Drop Size	
4.5	100	108	8.86	+7
4.5	200	60	4.76	+7
4.5	300	43	4.50	+5
4.5	400	34	4.45	+5
9.0	100	121	13.32	+6
9.0	200	72	8.73	+7
9.0	300	55	6.59	+7
9.0	400	46	4.58	+6
18	100	155	15.68	+5
18	200	107	13.45	+5
18	300	90	13.14	+6
18	400	81	13.27	+5
			Twice Nukiyama-Tanasawa Drop Size	
4.5	100	434	48.08	-12
4.5	200	241	33.06	-5
4.5	300	172	26.37	-2
4.5	400	137	22.23	0
9.0	100	483	50.52	-14
9.0	200	290	39.34	-9
9.0	300	221	32.79	-6
9.0	400	186	30.87	-3
18	100	621	61.18	-19
18	200	428	52.49	-16
18	300	360	50.65	-13
18	400	324	48.38	-12

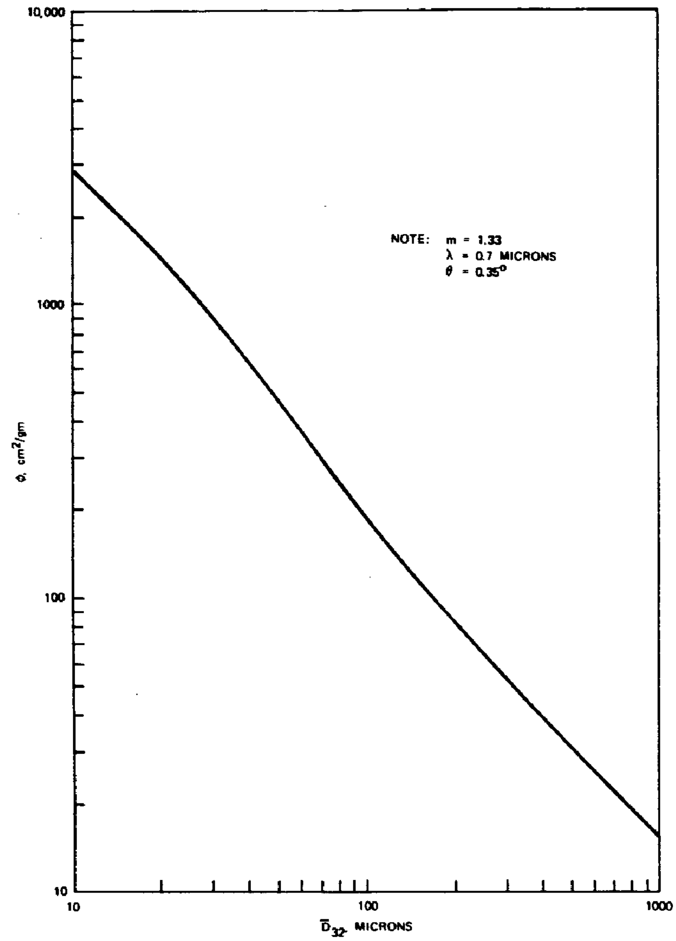

FIGURE 1 SPECIFIC EXTINCTION CROSS SECTION FOR WATER DROPS IN AIR

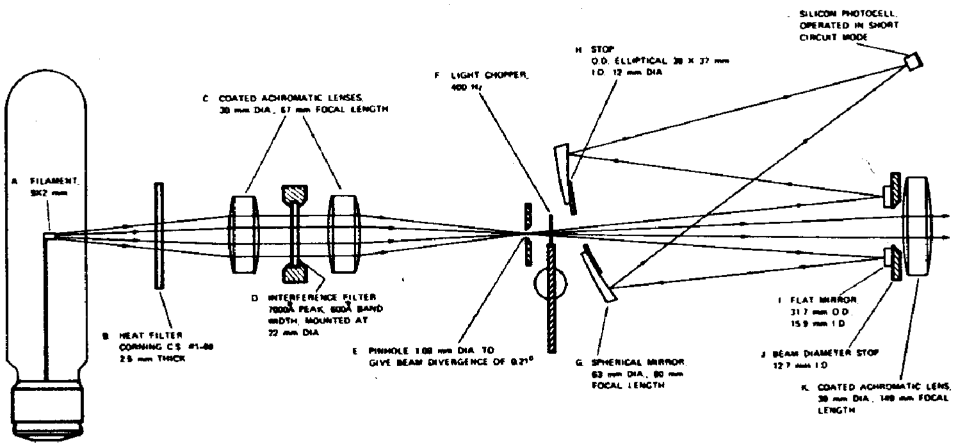

FIGURE 2 SOURCE OPTICS

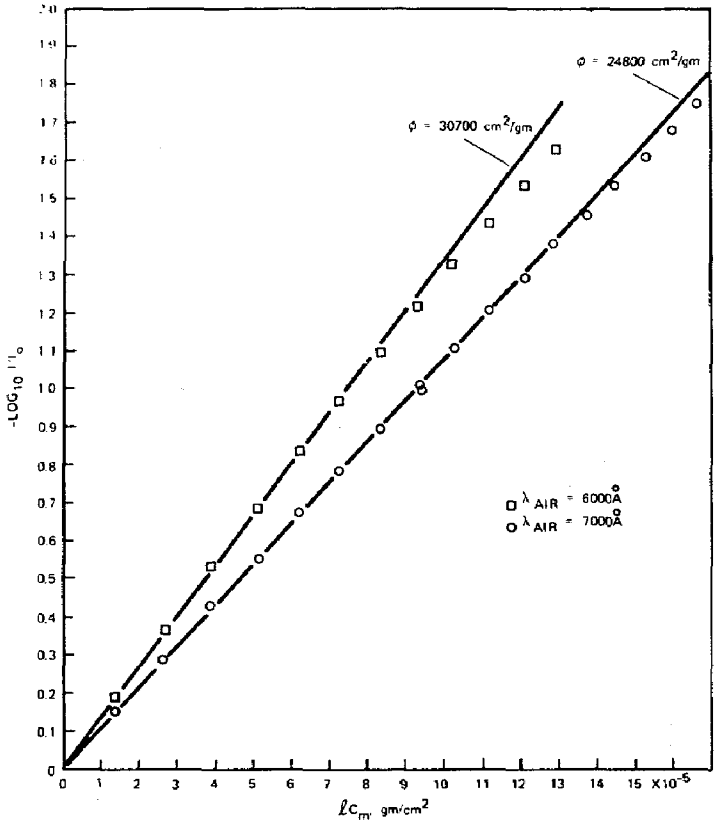

FIGURE 3 TRANSMISSION DATA FOR 0.714-MICRON BEADS

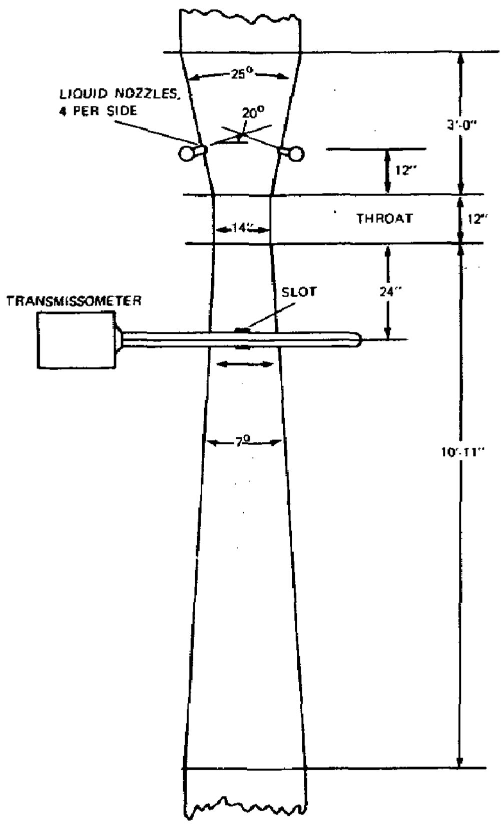

FIGURE 4 VENTURI CONFIGURATION

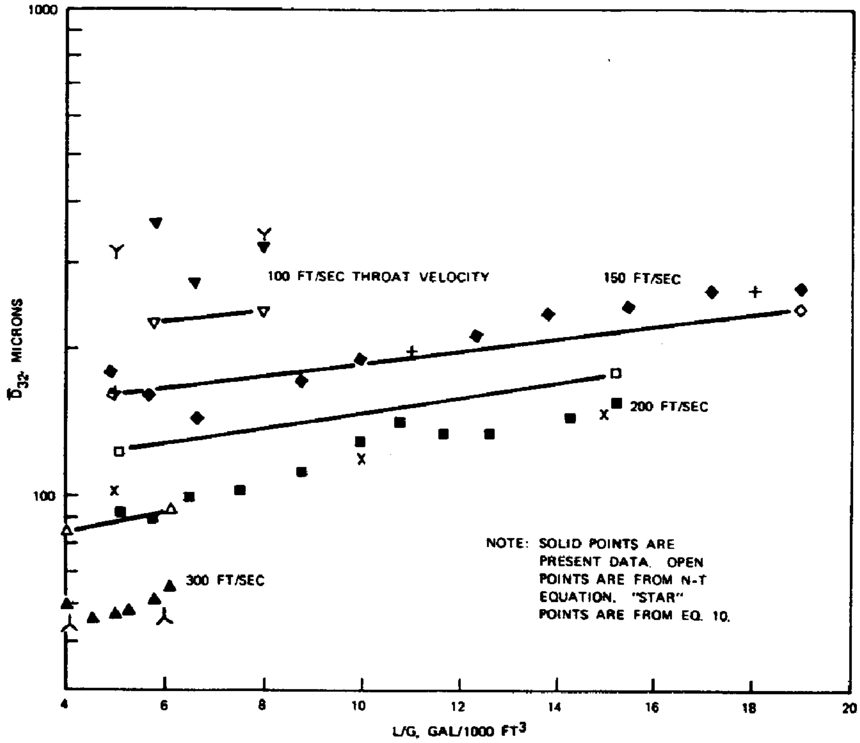

FIGURE 5 DROP SIZE RESULTS

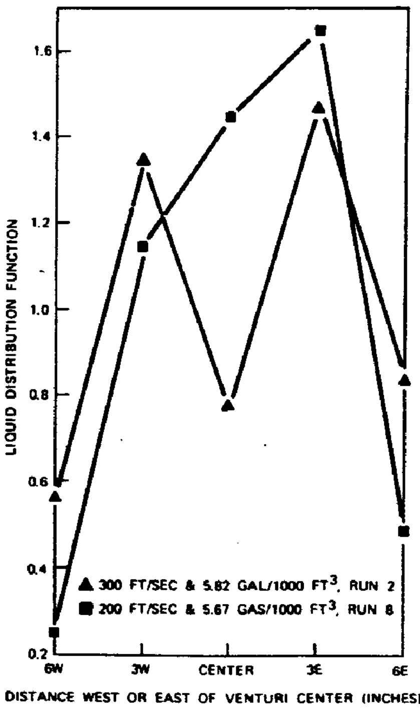

FIGURE 6 LIQUID DISTRIBUTION FUNCTION ACROSS VENTURI

FINE PARTICLE COLLECTION EFFICIENCY RELATED TO PRESSURE DROP, SCRUBBANT AND PARTICLE PROPERTIES AND CONTACT MECHANISM

by

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ABSTRACT

Collection efficiencies are shown for control of fine particles in venturi scrubbers (1) as a function of pressure drop and (2) as a function of throat area and liquid to gas ratio. A relationship of pressure drop to throat area, gas density, throat velocity and liquid to gas ratio is given and is used to provide a method for estimating efficiency knowing only these scrubber design parameters. The effect of charged particles and of surface active agents on collection efficiency are discussed briefly.

NOMENCLATURE FOR TERMS NOT OTHERWISE DEFINED

ACFM	=	actual cubic feet per minute of gas
C_o/C_i	=	ratio of mass concentration out to concentration in by weight, 1-E
ΔP	=	pressure drop across Venturi, inches water
E	=	collection efficiency fraction by weight, $1-C_o/C_i$
exp	=	signifies e (natural log base) to the exponent indicated by the quantity in brackets after exp
fps	=	feet per second
gr	=	grain, 1/7000 of a pound
ID	=	inside diameter
L	=	liquid to gas ratio, gal/1000 SCF
scfd	=	standard cubic feet of dry gas
scfm	=	standard cubic feet per minute at 70^{o}F and 1 atmosphere
μ	=	microns or micro meters

CONVERSION FACTORS

English to Metric Units

1 scfm	= 1.6 Nm^3/hr
1 gpm	= 0.227 m^3/hr
1 ft^3	= 0.0283 m^3
1 gal	= 3.785ℓ
1 gal/1000 ft^3	= 0.134 ℓ/m^3
1 grain/ft^3	= 2.29 g/m^3
1 ft/sec	= 0.3048 m/sec
1 in	= 2.54 cm
1 pound	= 454 grams

INTRODUCTION

It is extremely difficult to obtain accurate and reliable data related to the collection efficiency and operating pressure drop of venturi scrubbers. Those who are in the position of wishing to purchase one of these high efficiency wet scrubbing devices are usually confused by the differing unit sizes and operating conditions recommended by the various suppliers of venturi scrubbers. It is significant that a proper device be chosen because an underdesigned unit will result in failure to meet emission control requirements and an oversized unit could be much more costly than necessary to operate.

This paper presents results of industrial and laboratory studies and provides a method of more accurately estimating collection efficiency and pressure drop. Even though these data are the combination of an enormous amount of measurements and even though a new parameter (throat area) is included to make the prediction equations more accurate, it is anticipated that further refinements and improvements will be possible. Some of these prediction equations were presented in original form by Hesketh (1) at the U.S.-U.S.S.R. Symposiums on Control of Fine Particulate Emissions in January 1974.

PREVIOUS STUDIES

The recent Scrubber Handbook by Calvert (2) very thoroughly summarizes the studies and data related to efficiency and pressure drop in venturi scrubbers and other wet scrubbing systems. The study presents a method for estimating pressure drop through venturi scrubbers as a function of throat gas velocity and liquid to gas ratio (Equation 5.3.6-10, page 5-122). This theoretical equation was derived assuming that all energy is used to accelerate the liquid droplets to the throat velocity of the gas. The equation in metric units is:

$$\Delta P' = 1.03 \times 10^{-3} (v_t')^2 L' \qquad (1)$$

where: $\Delta P'$ = pressure drop, cm H_2O

v_t' = gas throat velocity, cm/sec

L' = liquid to gas ratio, ℓ/m^3

Calvert also presents a collection efficiency equation (Equation 5.3.5-6, p. 5-122). Several assumptions related to collection mechanism, slip, drag, size of the atomized droplet collectors and uniformity of the atomized liquid are used to develop the collection efficiency equation in terms of particle penetration, Pt. Penetration is defined as "one minus efficiency" and can be stated as 1-E or C_o/C_i, where C_o is mass concentration out of scrubber and C_i is concentration in. Calvert's Equation 5.3.6-5 is:

$$Pt = \exp\left[\frac{2\ L' v_t' \rho_\ell d_\ell}{55\ \mu_g} F(K_{pt}, f)\right] \qquad (2)$$

where: d_ℓ = diameter of atomized liquid droplet, cm
ρ_ℓ = density of liquid, g/cm^3
μ_g = viscosity of gas, g/(cm sec)

The expression $F(K_{pt}, f)$ is used to relate the effects of the inertial impaction parameter evaluated at the throat gas velocity, K_{pt}, and the "unknown factor, f".

The factor f is believed to relate non-uniformity of the atomized liquid and the resulting difference in the liquid and gas velocities. Ranges of f are suggested to be about 0.1 to 0.3 for hydrophobic aerosols and higher for hydrophilic aerosols. An average value of 0.25 is used for f in the graphs presented in the handbook.

Information related to pneumatic two fluid atomization and specifically as to whether atomization produces cloud type or drop type droplets is reported in previous studies (1,3,4). Study (1) relates this information to pressure drop in a 1,500 cfm pilot plant venturi scrubbing coal fly ash. These pressure drop data vs. throat gas velocity are presented here as Figure 1. The incomplete-complete atomization predictions are based on acceleration observations reported in the study.

These later data show that the pressure drop predictions obtained from throat velocity measurements may be subject to error at low velocities if an expression as Equation (1) is applied for all ranges of velocities. Utilization of available energy in atomization is poor (0.53% reported by Marshall (5) for drop-type atomization and 6.1% calculated for cloud-type atomization), but during the plateau shown on the curve in Figure 1, energy is being utilized to complete the atomization. On either side of this region, an increase in energy goes into creating system turbulence which is recorded as increased pressure drop. This 1,500 cfm system is a fixed throat venturi and was operated so as to produce cloud-type atomization. The data are for before the throat injection of the scrubbing water.

VENTURI SCRUBBER PRESSURE DROP

Pressure drop data were obtained from many fixed throat venturi scrubbers. These systems include 600 cfm laboratory units, 1,500 cfm pilot plant systems and commercial facilities as large as 300,000 cfm capacities. Various gases and particulate matter were present ranging from industrial emissions to combustion gases.

Evaluation and correlation of all data enabled the following equations to be developed by Hesketh (1) and which are restated here:

$$\Delta P = \frac{v_t^2 \rho_g A^{0.133}}{507} (0.56 + 0.125 L + 2.3 \times 10^{-3} L^2) \qquad (3)$$

$$\Delta P = \frac{v_t^2 \rho_g A^{0.133} L^{0.78}}{1270} \qquad (4)$$

where: ΔP = venturi pressure drop, inches water gauge

L = liquid to gas ratio, gal/1000 ACF

ρ_g = gas density downstream from venturi throat, lb/ft^3

v_t = throat velocity of gas, ft/sec

A = throat cross-section area, ft^2

Table I lists industrial venturi scrubber applications and gives the operating conditions. These data span a variety of scrubber sizes, pressure drops, throat velocities and liquid to gas ratios. Listed in this table are the pressure drops calculated using Equations (3) and (4) with the proper design and operating parameters and gas density. These ΔP data show good correlation with the measured values. Figure 2 shows that these equations also apply to 1,500 cfm venturi scrubbers.

Equations (3) and (4) are applicable to small 1,500 cfm venturi scrubbers. The full curve in Figure 2 (at L = 20) is measured data and Equation (3) fits this curve. The family of curves shown at other liquid to gas ratios were calculated using Equation (3).

These equations introduce two parameters (A and ρ_g) compared with Equation (1) which should be accounted for in this work. Throat area (or diameter) is a direct expression of system turbulence as revealed by its relation to Reynolds

TABLE I

VENTURI SCRUBBER DATA

EXAMPLE NUMBER	SATURATED GAS ACFM	SATURATED GAS TEMP, °F	THROAT GAS VELOCITY v_t ft/sec	LIQUID TO GAS RATIO L, gal/1000 ACF	DUST CONCENTRATION grains/SCF in	DUST CONCENTRATION grains/SCF out	THROAT AREA, A, ft^2	PRESSURE DROP, inches H_2O MEASURED	PRESSURE DROP, inches H_2O CALC. BY EQ. (3)	PRESSURE DROP, inches H_2O CALC. BY EQ. (4)
1	274,000	126	100	20	/	/	45.7	6.9	9.1	9.5
2	50,000	164	100	40	8	0.1	8.33	10	12.3	13.0
3	50,000	164	175	14	8	0.04 (a)	4.76	20	14.4	16.3
4	185,000	177	200	15	3	0.05	15.42	35	29.3	32.8
5	60,000	105	100	6	0.61	0.05	10.00	5	2.6	3.0
6	225,000	135	360	14	4	0.005	10.42	60	57.9	65.5
7	280,000	125-187	350	6-15 (b)	5	0.005	13.33	60	/	/
8	90,000	125-187	350	6-15 (c)	5	0.005	4.29	60	/	/
9	41,400	130	350	16.9	8	0.03	1.97	55	52.0	57.4
10	54,000	325	230	15	/	/	3.91	28	25.8	28.9

NOTES: (a) Guaranteed outlet concentration, no test made.
(b) Calculate L = 10.5 using Eq. (4)
(c) Calculate L = 12.8 using Eq. (4)

APPLICATIONS ARE: 1-Cyclone Boiler, 2-Lime Kiln, 3-Lime Kiln, 4-Black Liquor Recovery Boiler, 5-Fly Ash Sinter Furnace, 6-Blast Furnace, 7-Blast Furnace, 8-Blast Furnace, 9-Foundry Cupola, 10-TPA Processing.

number. This parameter may help solve the problem experienced by use of the "unknown factor f" that appears in Equation (2). Venturi pressure drop is directly effected by gas density, and though small, it should be accounted for. Caution must be exercised to be sure the system is operated at non-scaling and non-plugging conditions, the pressure lines are properly cleared and the pressure drop readings are completely valid.

The data used for Equations (3) and (4) were obtained from units operated so as to produce cloud type atomization and are for venturi scrubbers that have liquid injected before the throat. When the same amount of liquid is injected at the throat, data available so far indicate that the ΔP is somewhat higher (up to 10%).

No factor for liquid properties is included in Equations (3) and (4). Most of the data for these equations were obtained using river water, but some chemical scrubbants were used. Further data are needed to determine the effects on ΔP of variations in liquid density, viscosity, composition and particle wettability.

Fine Particles and Collection Efficiencies

Fine particles in this work are considered to be all particles 5 microns or smaller in size. It is considered that the venturi scrubber is 100% efficient for the removal of particles larger than 5μ. The penetration, which is one minus collection efficiency of particles, is expressed as C_o/C_i where C_o and C_i are respectively the weight concentration of less than 5 micron particles out and into the venturi scrubber.

The value for C_i is established by multiplying the inlet dust loading by the weight fraction of particles that are 5 microns or less in size. These values are obtained from literature such as Reference (2) assuming log mean particle size distribution and are listed in Table II. For example, the amount of foundry coupola dust 5μ and smaller in size is assumed to be 0.14 times the scrubber inlet dust loading.

Note that inlet dust loadings may be subject to considerable variation and therefore, in some cases, an average inlet concentration must be used. The blast furnace data in example numbers 7 and 8 are averages as the reported inlet loadings range from 3-7 grains/scf.

The data in Table I are relisted in Table II and the measured ratios of C_o/C_i for <5μ particles are calculated and listed for the various open throated venturi scrubbers. A very distinct trend can be seen when these ratios are plotted against venturi pressure drop as in Figure 4. These data are marked + in Figure 4.

Some unpublished Swedish removal efficiency data for venturi scrubbers and non-charged particles were obtained. These data, which represent many hundreds of industrial data points, give removal efficiency as a function of particle size for various venturi scrubber pressure drops. Assuming that typical fine industrial particles have a geometric size distribution, a mean diameter by weight of about 1 micron and an approximate standard deviation of 3.9, it is possible to estimate overall collection efficiencies using the Swedish data. These efficiencies were calculated by graphical integration and are shown as C_o/C_i by the "dots" in Figure 3. The line drawn through these dots agrees well with the other measured efficiency data for collection of fine particles.

Fine Particle Collection Equations

Actual fine particle collection efficiencies would depend on numerous parameters as shown in Equation (2). Liquid, gas and particle properties need to be considered as well as equipment design and operating conditions. However, for approximating fine particle collection efficiencies, Figure 4 shows that good estimates should be possible if accurate pressure drop data are obtained.

Collection efficiency (E) of particles <5μ in size expressed as penetration (1-E) is approximately related to pressure drop by the line in Figure 3 which is given as:

$$C_o/C_i = 3.47\ \Delta P^{-1.43} \tag{5}$$

where: ΔP = pressure drop, inches of water

Combining this equation with Equation (4) which has been shown to be an accurate method for predicting pressure drop, gives:

$$C_o/C_i = \frac{9.52 \times 10^4}{v_t^{2.86}\rho_g^{1.43}A^{0.190}L^{1.12}} \tag{6}$$

Equation (6) is good for the collection of fine, non-charged particles.

Equation (6) efficiency predictions agree better with the Table II dusts than for the particulates formed as fumes. The fumes may be charged because of their method of formation. The scatter of data that are present are compounded when Equations (4) and (5) are combined in Equation (6) and further, accurate test data will be useful to show how these relationships should be corrected, if necessary. Diffusiophoresis and Stephan flow factors are not considered in these equations. As more data become available, it may be possible to add modifications to account for these effects.

With the relationship given as Equation (6), it is possible to predict approximate collection efficiencies of fine particles by venturi scrubbers by specifying only the design parameters of throat velocity (v_t, ft/sec), throat area (A, ft^2), gas density (ρ_g, lb/ft^3) and liquid to gas ratio (L, gal/1000 ACF).

TABLE II

VENTURI SCRUBBER COLLECTION EFFICIENCIES FOR <5 MICRON PARTICLES

EXAMPLE NO.	WT. FRACTION DUST ORIGINALLY <5μ	DUST CONCENTRATION, grains/SCF		C_o/C_i FOR <5μ		
		C_i	C_o	MEASURED	CALCULATED BY EQ. (6)	PREDICTED BY EQ. (8)
2	0.17	1.36	0.10	0.074	0.087	.0009
3	0.17	1.36	0.04	0.029	0.062	.0018
4	0.60	1.80	0.05	0.028	0.021	.0012
5	0.10	0.06	0.05	0.833	0.706	.0032
6	0.45	1.80	0.005	0.0028	0.009	.0028
7	0.45	2.25	0.005	0.0022	0.012	.0026
8	0.45	2.25	0.005	0.0022	0.012	.0022
9	0.14	1.12	0.03	0.027	0.010	.0023
10	0.30	/	/	/	0.031	

It should be pointed out that a simplified relationship is available for predicting changes in the ratio C_o/C_i. The study in Reference (1) reveals that:

$$C_o/C_i \propto A^{-0.092} L^{-1.39} \tag{7}$$

The data in Tables I and II are plotted in Figure 4 to show how these data relate to the equation (7) proportionality. The three points at the bottom of this figure are the blast furnace data, example numbers 6, 8 and 7, in that order, from left to right.

Charged Particle Collection

Quite frequently, venturi scrubbers have been installed following electrostatic precipitators for one reason or another. The fine particles that pass through precipitators that are operating are electrically charged. These charged particles are more efficiently collected by venturi scrubbers and some of this data is now being obtained from these installations.

Reference (1) presents a fine particle collection efficiency prediction equation for venturi scrubbers. Much of these data were obtained using charged particles and, as a result, the equation is applicable to collection of fine charged particles. This equation is restated below as Equation (8):

$$C_o/C_i \cong 3.45 \times 10^{-7} v_t^{3.56} A^{0.145} \left(\frac{\rho_g}{\Delta P}\right)^{1.78} \tag{8}$$

The efficiencies predicted by Equation (8) for non-charged, non-metallic dusts are in error by being too high compared with the measured or Equation (6) values. However, the efficiencies predicted by Equation (8) for metallic fumes are in good agreement with the measured values. The metallic fumes probably are charged because of their method of formation. Equation (8) has not been tested and more work is needed to determine the reliability.

Use of Wetting Agents in Scrubbers

Wetting agents or surfactants reduce the surface tension of the liquid and if properly used, improve particle collection by not only making the atomization occur easily but also by enhancing particle wettability. Several non-ionic, low foaming surfactants were studied and the optimum results were obtained using 0.1% by weight Rohm and Haus Triton CF-10 which reduced the water surface tension to about 10 dyne/cm at room temperature. The results of this study are also reported in Reference (1) along with the equation:

$$C_o/C_i \cong 8.42 \times 10^{-8} v_t^{3.87} A^{0.157} \left(\frac{\rho_g}{\Delta P}\right)^{1.93} \quad \text{(for water + wetting agent)} \qquad (9)$$

This equation has the same reservations as Equation (8) and needs to be tested further.

During the study, the use of the wetting agent CF-10 did decrease outlet dust loadings by about 50%. Outlet dust loadings ranged from 0.001 to 0.0093 grains/scf and inlet dust was 2.5 grains/scf.

SUMMARY AND CONCLUSIONS

It appears that fine particle collection efficiency in a venturi scrubber is closely related to scrubber throat pressure drop. A large amount of industrial data was extrapolated to establish the efficiency for <5μ dust and from this, Equation (5) was developed:

$$C_o/C_i = 3.47 \; \Delta P^{-1.43} \qquad (5)$$

Using both industrial and research pilot data, new equations are developed for accurately predicting venturi scrubber throat pressure drop for open throat, non-plugging and non-scaling systems where the liquid is injected before the throat. These equations (3) and (4) include the important parameters of venturi throat area and gas density as well as the throat gas velocity (at the saturated gas temperature) and the liquid to gas ratio. No equation is given for predicting pressure drop when the water is injected at the throat, but it appears that this causes about a 10% higher ΔP.

The combination of the efficiency and pressure drop equations makes it possible to predict fine particle collection efficiency knowing only the design parameters of throat velocity and area, gas density and liquid to gas ratio. Equation (6) is developed for this purpose and appears good for non-charged particles. Charged particles have a greater collection efficiency and Equation (7) is given for this. More work is needed to establish the reliability of these equations.

Wetting agents can also improve collection efficiency and preliminary studies show that dust loadings can be reduced by as much as 50%. It is important to use non-foaming surfactants.

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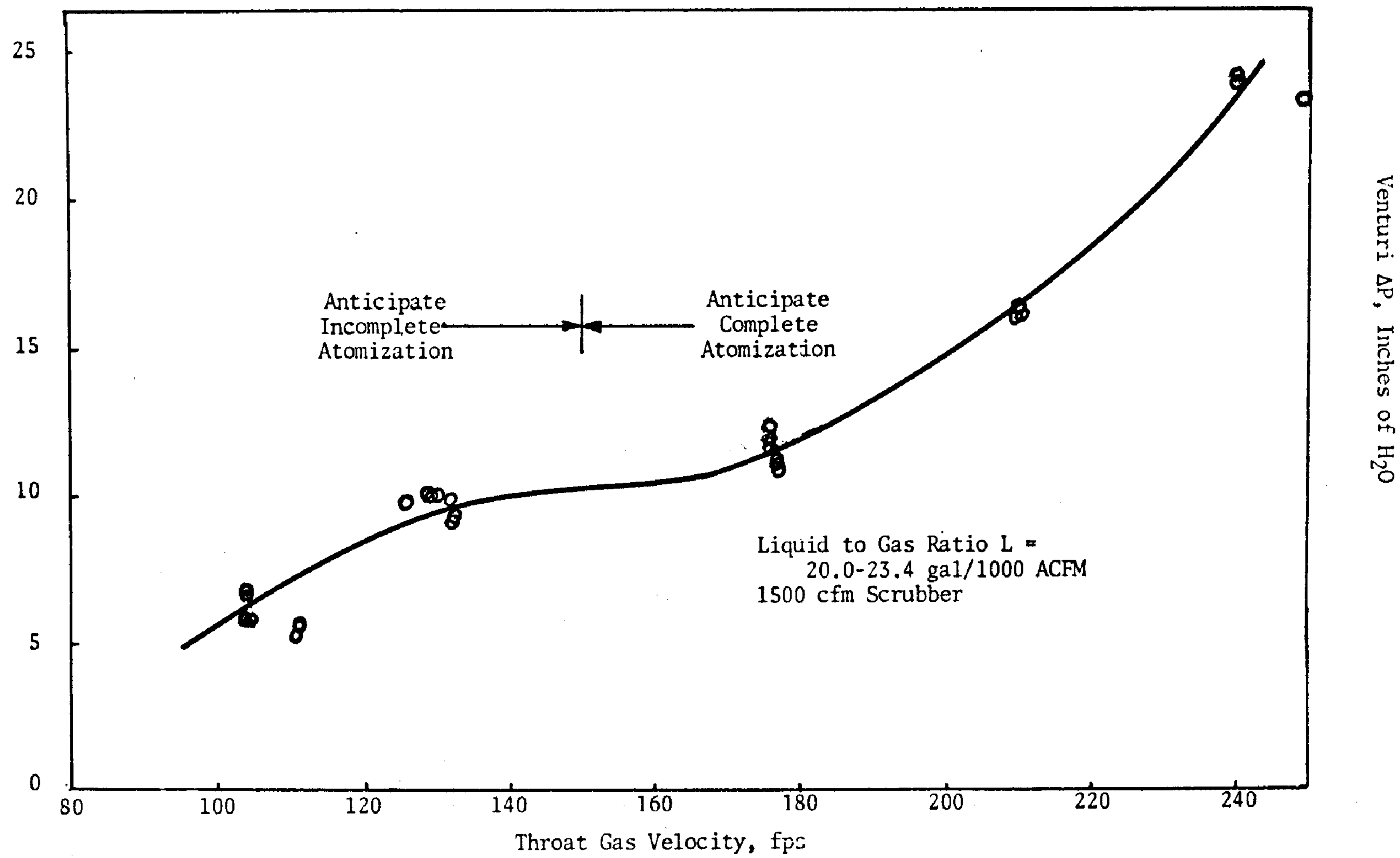
FIGURE 1

VENTURI SCRUBBING OF COAL FLY ASH AFTER ELECTROSTATIC PRECIPITATOR



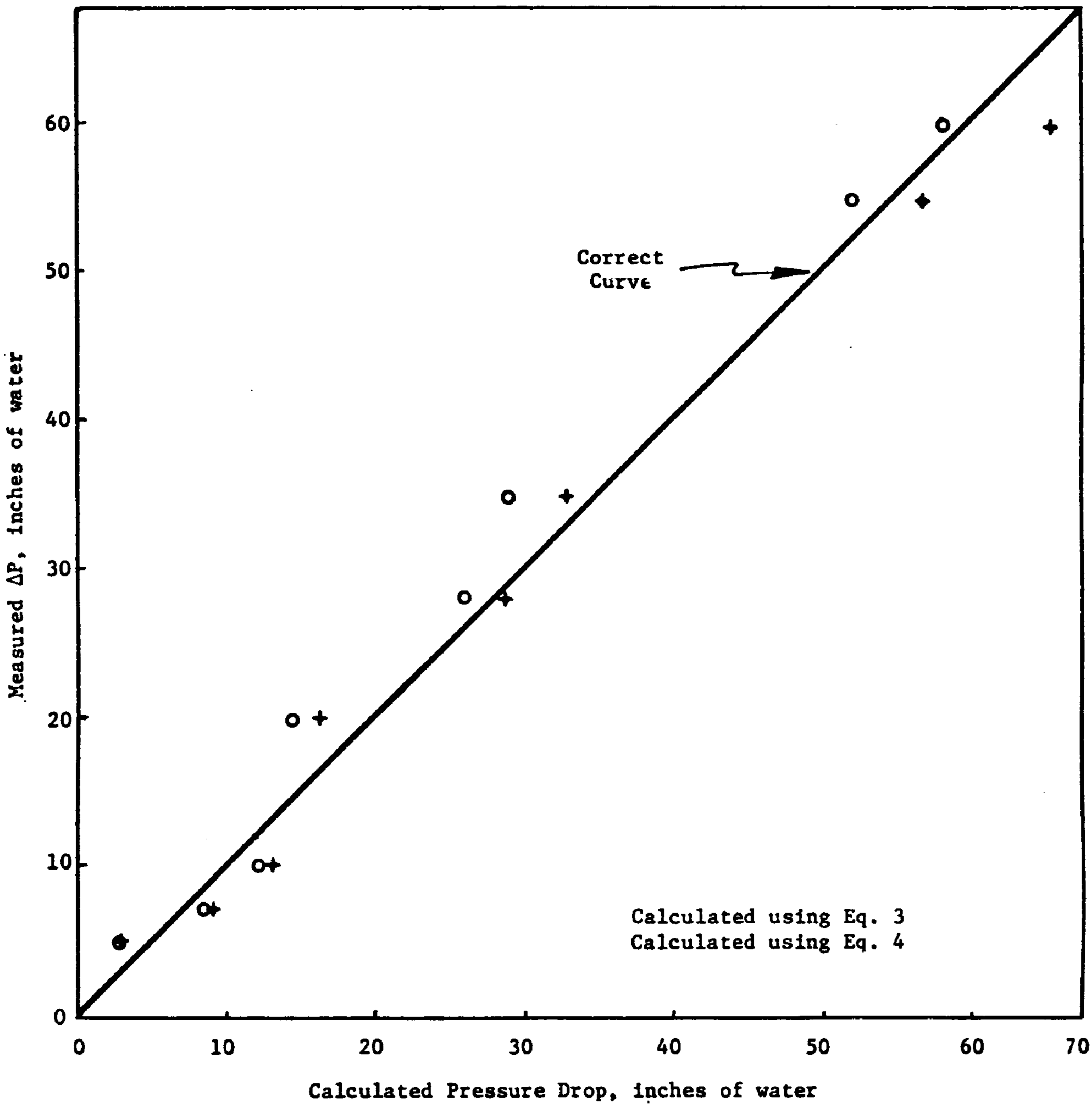
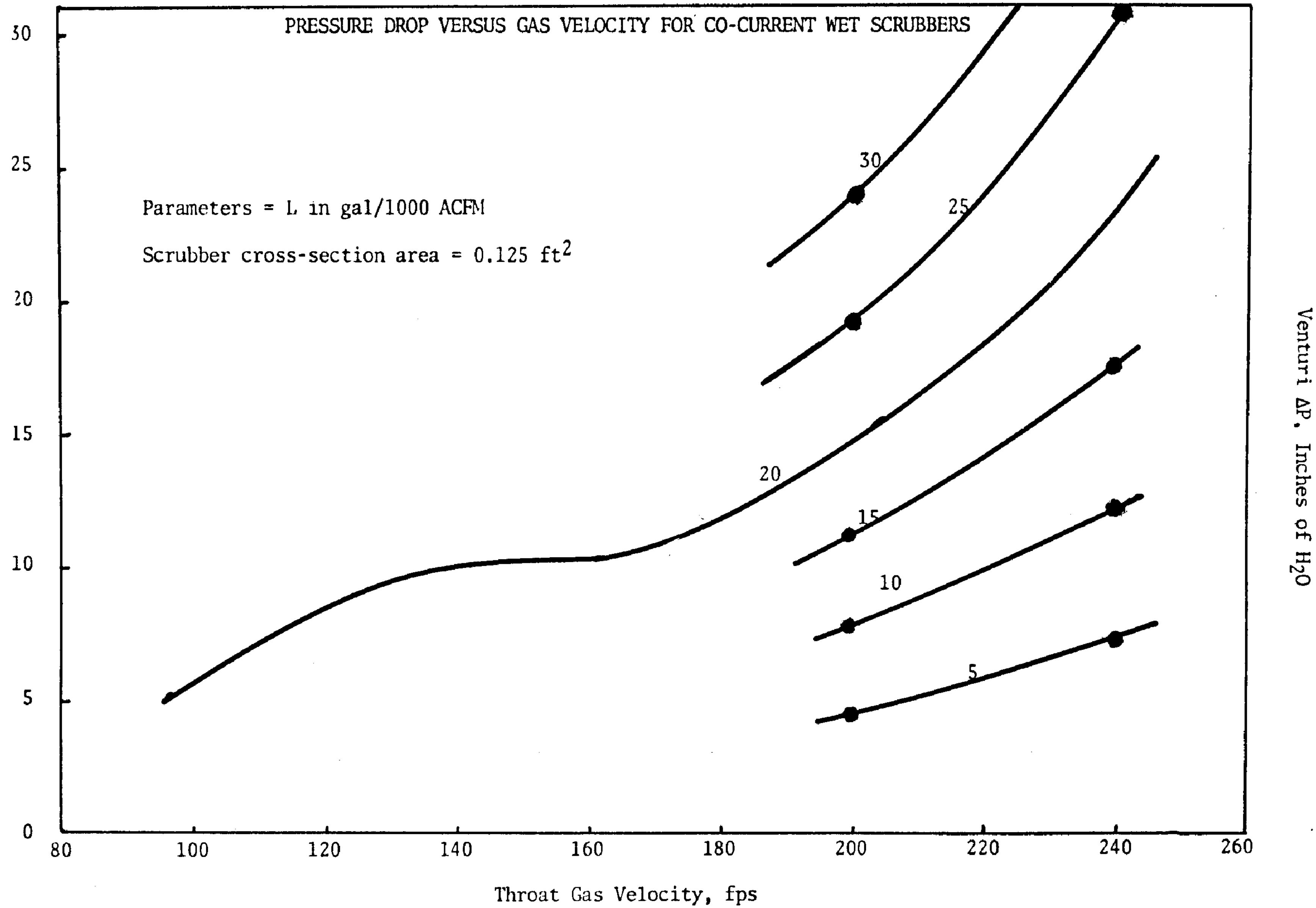


FIGURE 2

COMPARISON OF INDUSTRIAL VENTURI SCRUBBER MEASURED PRESSURE DROP AND PREDICTED PRESSURE DROP CALCULATED BY EQUATIONS [3] and [4]

FIGURE 3



PRESSURE DROP VERSUS GAS VELOCITY FOR CO-CURRENT WET SCRUBBERS

FIGURE 4

VENTURI SCRUBBER FINE PARTICLE COLLECTION EFFICIENCY VS PRESSURE DROP

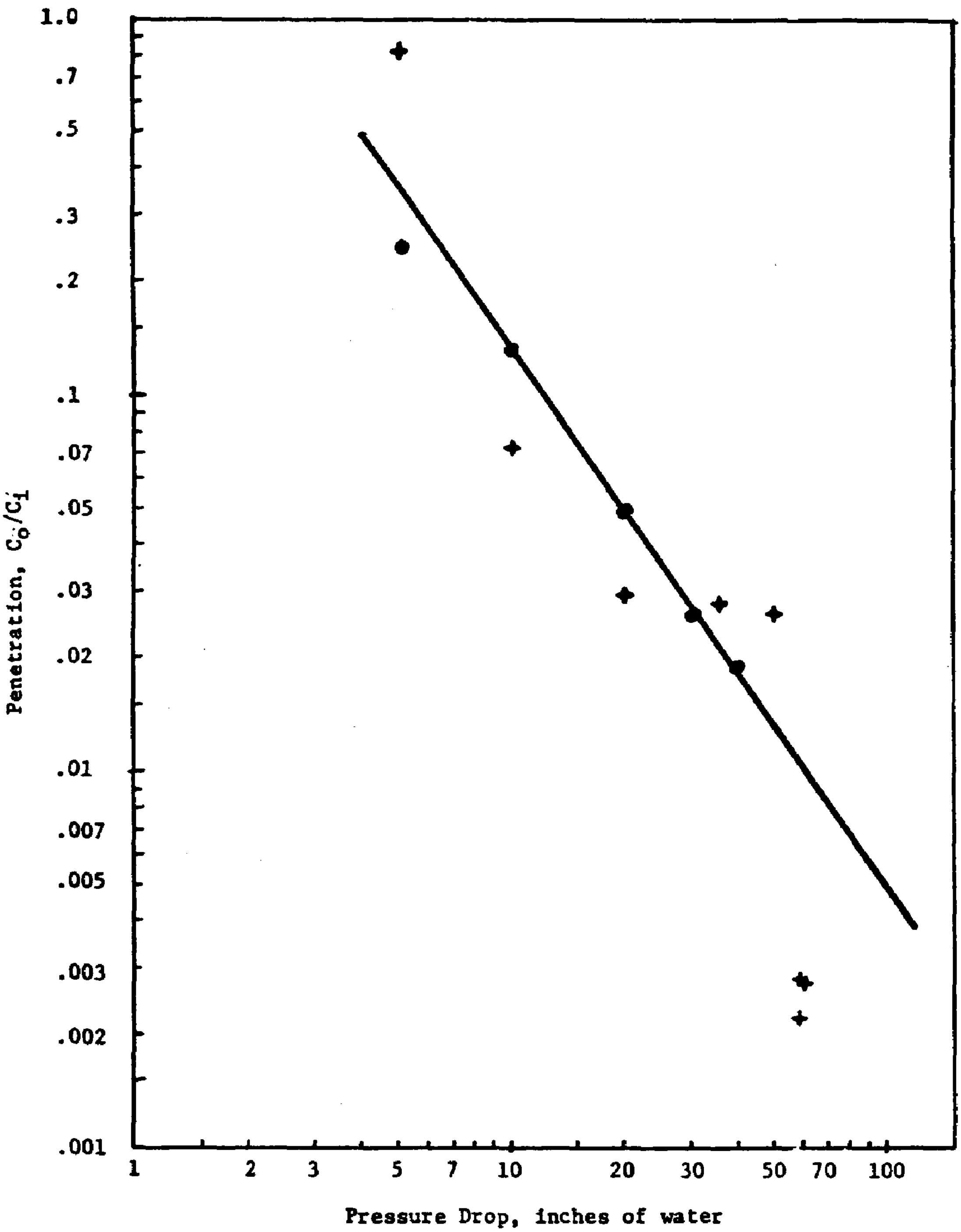
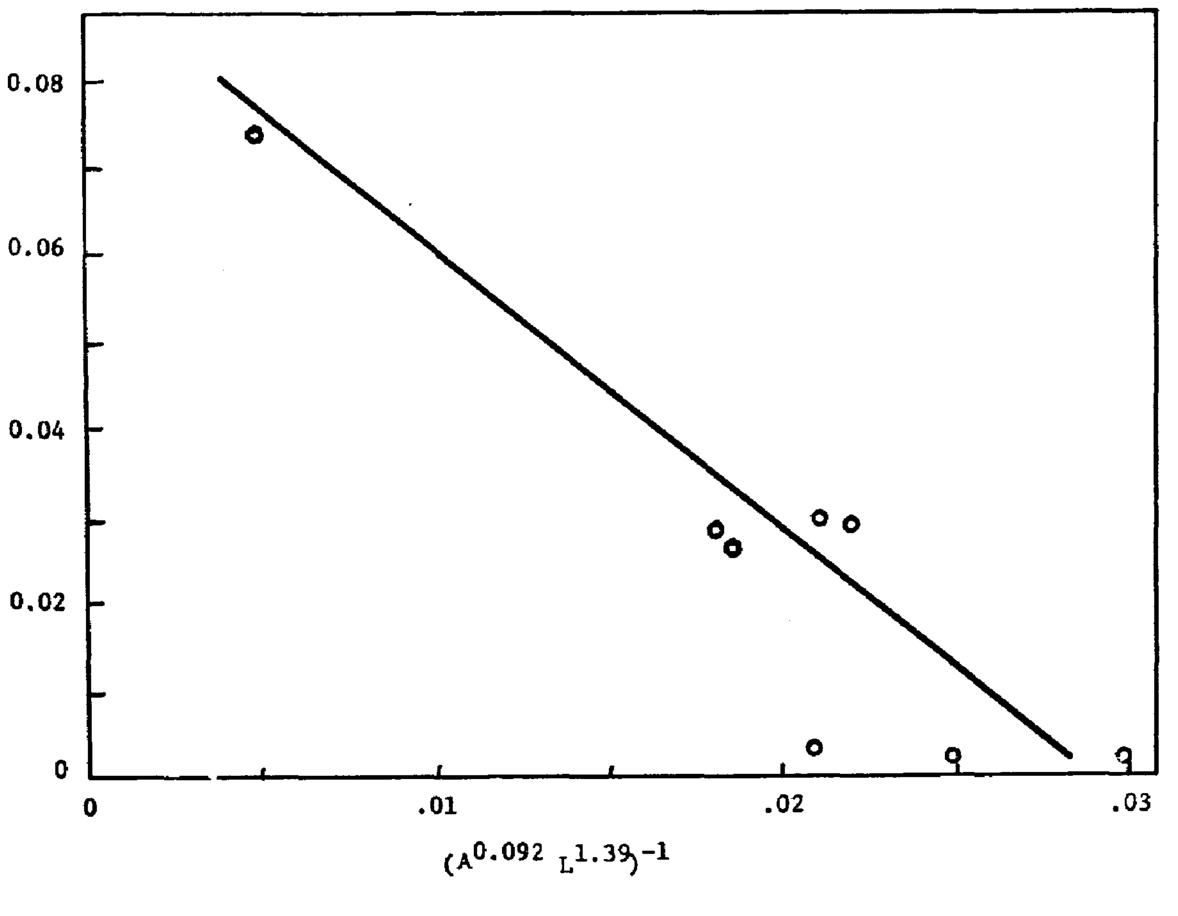


FIGURE 5

FINE PARTICLE COLLECTION EFFICIENCY
IN A VENTURI SCRUBBER AS A FUNCTION
OF THROAT AREA AND LIQUID TO GAS RATIO



EFFECTS OF WATER INJECTION ARRANGEMENT ON THE PERFORMANCE OF A VENTURI SCRUBBER

by

S. W. Behie and J. M. Beeckmans

ABSTRACT

The effect of three different arrangements of two water manifold injection systems on the performance of a venturi scrubber was studied. Velocities ranging from 23.4 to 49.7 m/sec were used with aerosol diameters of 0.8, 1.6, 2.9 and 5.0 microns. Scrubber efficiency was found to be larger than predicted theoretically with the larger particles, and smaller than predicted theoretically with the smaller particles. The spacing, diameter, and location of the injection orifices were found to have an effect on scrubber efficiency.

INTRODUCTION

Although venturi scrubbers have been used to combat particulate emissions in various industries for almost thirty years, it has only been recently that advances in basic knowledge of scrubber operation have been made. These advances have been made possible by the use of monodispersed aerosol particles which has allowed some reliable basic data on venturi scrubber efficiency to be obtained [1-3]. (Mathematical models of venturi scrubbers can only be properly tested with data of this nature.) In addition insight has been gained into the atomization process occurring within the scrubber throat [4-7]. Since aerosol capture is due mainly to inertial effects requiring good aerosol-droplet contacting, one would expect that a requisite for good scrubber performance would be complete initial coverage of the scrubber by the atomized droplets. In fact the increase in aerosol capture efficiencies of large units over smaller units of similar design has been explained on the basis of better initial coverage of the larger unit by the atomized spray [8,9]. One would expect that investigators not reporting this trend (Semrau et al. [10], Collins [11], Bassé [12], Mellor and Stevens [13], Johnstone and Roberts [14], West [15], Walker and Hall [16]) ensured good coverage of the throat in both units. Of course, increased pressure drops (power consumption) goes hand in hand with improved initial coverage.

The relative performance of venturi scrubbers for different water injection methods has been reported. In a few cases slight differences in performance were measured [9,17] for the three quite different water injection methods used. From experiments conducted on a much larger unit [18], the same scrubber performance was reported using three different water injection methods. Despite the fact that the initial throat coverage as measured photographically was poor (between 40-50%), efficiencies greater than 90% (2.3 transfer units) were reported. The highly turbulent flow pattern of the gas, promoting intimate mixing, was stated as the reason for this behavior. Although the importance of turbulence has been supported by other authors [16,17,19], one would expect its effect to be felt only in situations of incomplete contacting (poor initial throat coverage). For a state approaching complete mixing the intimate contacting between the aerosol and water droplets precludes any need to transport the aerosol particles through turbulent diffusion to the water droplets.

At this time we are reporting results obtained with a pilot plant scale venturi scrubber using experimental techniques similar to those recently reported [3]. Three different water injection arrangements of two different manifold systems were studied for throat velocities ranging from 23.4 to 49.7 m/sec. In each case monodispersed uranine-methylene blue particles having diameters of 0.8, 1.6, 2.9 and 5.0 microns, and density 1.42 g/cm^3 were used.

APPARATUS

The experimental apparatus used in this study was quite similar to that used in our previous recently published study [3], with a few notable differences. It consisted of a venturi scrubber, followed by a cyclonic demister. Aerosol particles were generated by a spinning disk aerosol generator, and passed into a 20 cm diameter pipe, 1.5 m in length. Sampling was isokinetic, at the end of the pipe, just prior to entry to the scrubber. The gas passed from the cyclone into an involute chamber, which served to remove the vorticity induced by the cyclone. A 1.5 m length of 20 cm pipe followed the involute chamber, and the aerosol was sampled isokinetically at the end of this pipe. In runs made to measure the demister efficiency, the aerosol was introduced downstream from the scrubber. The plexiglass test section, 127 cm long, had throat dimensions of 19.0 cm width by 6.45 cm depth, and was 7.62 cm in length. The total converger angle was 25° while that of the diffuser was 7°. In this study, the system was on the suction side of a centrifugal blower, thus eliminating the high temperatures produced in the previous system operating on the pressure side of a centrifugal blower. Except for minor changes, the remaining experimental set-up and aerosol sampling system were the same.

Water was injected into the throat of the venturi through several arrangements of two different manifold systems. Figure 1 shows a section through the throat of the scrubber, in planes normal and parallel to the gas flow, while descriptions of the manifolds are given in Table I.

THEORETICAL CALCULATION OF AEROSOL CAPTURE AND PRESSURE DROP

The basic calculation techniques used in the theoretical model have recently been described elsewhere [3], and are similar in nature to the methods of Calvert [1] and of Boll [20]. The equations of particle motion and of inertial impaction were integrated numerically for specific cases, taking into account scrubber geometry. This model assumes that a state of perfect mixing exists between gas and water droplets in planes normal to the flow direction, as well as the fact that no water reaches the scrubber surfaces. As such one would expect theoretical results predicted by this model to be higher than the corresponding experimental results, since maldistribution in the droplet flux would result in paths through the scrubber in which the flux is low, or in which the relative velocity between gas and spray is low, or both. Two different expressions were used for the drag coefficient, one being the Ingebo relation [21], the other an analytical representation for the standard drag curve [22].

The major factor contributing to the overall pressure losses encountered in a venturi scrubber is the energy expended in accelerating the water droplets. The pressure loss due to this factor over a differential time interval dt equals

$$dP = -\left(\frac{6\rho_F}{\pi D_p^3 \rho_p}\right)\left(\frac{1}{2} C_D \rho \ (V - V_p)^2 \ \frac{\pi D_p^2}{4}\right)dt$$

where ρ_F is the mass flux of droplets, D_p, V_p, ρ_p the droplet diameter, velocity, and density, V, ρ, the air velocity and density and C_D, the instantaneous drag coefficient.

Integration with respect to time over the throat and diffuser of the scrubber gives the overall pressure loss due to momentum transfer to the spray. During those time increments over which the water droplets, because of their inertia, move faster than the air, momentum transfer is to the air, thus representing a recovery term. Other factors such as friction losses through system and the atomization process cause pressure losses which are quite small in comparison and are discussed in detail elsewhere [25]. Frictional losses were taken into account by assuming 88% recovery of the converger pressure loss in the dry system. Boll [20] describes a fundamental approach to frictional losses in venturi scrubber.

RESULTS AND DISCUSSION

Efficiencies in transfer units $[N_T = - Zn(1-\eta)]$, for the scrubber-cyclone combination and for the cyclone separately, plotted linearly against water loading; Figure 2 shows a typical set of results for a specific aerosol particle size, throat velocity and manifold arrangement. Since the efficiencies of serial units, when expressed in transfer units, are additive, the transfer unit efficiency of the scrubber is obtained as the difference between the two curves shown in Figure 2. Similarly, the difference between the slopes of the two curves equals the slope of the curve of transfer unit efficiency of the scrubber against water loading. The experimental results are summarized in this form in Table II, the values in the table being computed by a linear regression analysis on the data points. Table III shows ratios of experimental to calculated slopes, using both the Ingebo and the standard drag expressions; these results are for arrangement O. The droplet sizes used in these calculations were based on the Nukiyama-Tanasawa equation [23]. It should be noted that the latter equation predicts an effect of water loading on droplet size, and as a result the theoretical curves were not completely linear; however the curvature was so slight as to be barely detectable visually, and a mean value was used.

Several pertinent conclusions may be drawn from a perusal of Table III. Perhaps the most interesting is that the theory in some circumstances underestimates scrubber efficiency substantially, particularly with large aerosol particles. Calculations indicate that with particles 3 μm or larger, particle size has little effect on theoretical scrubber efficiency; presumably this is because the relative velocity between aerosol particles and spray droplets in the throat, where most of the aerosol capture occurs, is so large that the single particle capture efficiency approaches unity. Downstream from this region, where the relative velocity is reduced to the point where particle size can affect single particle capture efficiency, the droplets move nearly as rapidly as the gas and the time of effective scrubbing by droplets in this region is very short. The experimental results are clearly at variance with this view, since scrubber efficiency increased considerably with the 5.0 μm particles over the 2.9 μm particles, under all conditions. The reasons for this phenomenon are far from clear, but they must be related to the mechanics of the jets, which have been shown to behave very differently from the concept of isolated droplets evenly dispersed in a gas having a uniform velocity distribution throughout the cross-section [6,7]. These studies have shown that droplet acceleration rates in the sprays are much slower than would be expected on the basis of particle size and mean air velocity, and that a considerable resistance occurs to transport of momentum from the air to the bulk of the droplets at the interior of the spray. Under these conditions, slower acceleration of droplets would occur, over a longer period of time, which would probably result in increased aerosol capture with the larger particle sizes. With small aerosols the slower droplet acceleration may result in such low single particle impaction efficiencies that overall aerosol capture efficiency in the scrubber would be adversely affected. This was in fact observed, particularly at the lowest velocities, but inefficient throat coverage by the spray may also have been partly responsible. It should be noted that in studies on aerosol capture by glass beads in a vertical pneumatic transport line, which is in many respects similar to the venturi scrubber, no anomalous effects were found and theory and experiments were in basic agreement [24]. The major difference between the two situations appears to be that the water is injected in coherent jets in the scrubber, whereas in the pneumatic transport line the glass beads were injected more or less evenly over a column cross-section.

A conclusion which may be drawn from Table II is that scrubber efficiency was higher in nearly all cases with manifold 1 (0.5 mm orifices) than with manifold 2 (2.0 mm orifices). The reason is thought to lie in better throat coverage with the more closely spaced orifices in manifold 1, but other factors may be involved, such as the nature of the atomization (Manifold 1 resulted primarily in drop-type atomization, whereas manifold 2 gave rise mostly to cloud-type atomization). In general injection of water from one side only of the scrubber (arrangement 1) resulted in the highest efficiencies. The reduced number of injection holes implied a corresponding increase in the injection velocity of the water, and a higher water injection pressure. The energy required to inject the water was small, however, compared with the energy losses by the gas phase in the scrubber.

Typical pressure drop results (expressed in the number of converging section heads) are shown in Figure 3 for the three arrangements of both manifolds at a mean air velocity of 49.7 m/s. There were little consistent differences in pressure drop for the different arrangements. Good agreement with theory is noted. Table IV shows a comparison of theoretical and experimental pressure drop data (for all velocities) in terms of slopes. The experimental slopes were computed by regression analysis on the data. The reverse trend of the experimental pressure drop data at the lowest velocity was due to increased reentrainment of water from the top diffuser surface; at this velocity more water penetrated directly to the diffuser surfaces.

It should be noted that both theoretical and experimental pressure drop results expressed even in this manner are functions of throat velocity. This fact has been overlooked by some investigators [8,10] when comparing published pressure drop data from several sources.

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TABLE I

SCHEDULE OF WATER INJECTION ARRANGEMENTS

	NUMBER OF UPPER ORIFICES	NUMBER OF LOWER ORIFICES
MANIFOLD 1 (0.5 mm ORIFICES)		
Arrangement 0	14	15
1	0	15
2	7	8
MANIFOLD 2 (2.0 mm ORIFICES)		
Arrangement 0	8	7
1	0	7
2	4	3

TABLE IV

PRESSURE DROP DATA

	SYSTEM SLOPE (M^3/KG)	
THROAT VELOCITY (m/s)	EXPERIMENTAL	THEORETICAL
23.4	0.55	0.25
34.1	0.45	0.85
41.2	0.85	1.00
49.7	1.25	1.15

TABLE II

EXPERIMENTAL RESULTS IN TERMS OF SLOPE
(TRANSFER UNITS/WATER LOADING, M^3/KG)

		MANIFOLD L			MANIFOLD 2		
THROAT VELOCITY (m/s)	AEROSOL DIA. (m)	ARRANGEMENT 0	1	2	ARRANGEMENT 0	1	2
23.4	5.0	5.4			2.6		
	2.9	1.8			0.81		
	1.6	1.2			0.33		
34.0	5.0	11.3		10.3	6.7	9.1	8.6
	2.9	5.1	5.0	4.8	3.4		
	1.6	2.1	1.4	1.7	1.1	1.2	1.1
	0.8	0.72			0.9		
41.2	5.0	22.2			10.8		
	2.9	8.6			5.9		
	1.6	3.6			1.6		
	0.8	1.25			1.0		
49.7	5.0	34.6			18.2		
	2.9	16.8	18.7	12.8	8.5	12.5	10.1
	1.6	7.6			4.5		
	0.8	2.8	5.1	3.7	1.8	2.9	2.6

TABLE III

COMPARISON OF EXPERIMENTAL AND THEORETICAL RESULTS

		SLOPE RATIO (EXPERIMENTAL/THEORETICAL)			
THROAT VEL(m/s)	AEROSOL DIA. (m)	MANIFOLD 1		MANIFOLD 2	
		(INGEBO DRAG)	(STANDARD)	(INGEBO)	(STANDARD)
23.4	5.0	1.24	2.03	0.59	0.98
23.4	2.9	0.49	0.84	0.22	0.38
23.4	1.6	0.50	0.97	0.13	0.26
34.0	5.0	2.07	3.2	1.23	1.9
34.0	2.9	1.04	1.7	0.70	1.1
34.0	1.6	0.56	0.97	0.30	0.53
34.0	0.8	0.40	0.84	0.51	1.1
41.2	5.0	3.7	5.7	1.8	2.8
41.2	2.9	1.6	2.5	1.1	1.67
41.2	1.6	0.82	1.33	0.37	0.61
41.2	0.8	0.53	1.24	0.42	0.99
49.7	5.0	5.2	7.9	2.9	4.1
49.7	2.9	2.7	4.2	1.4	2.1
49.7	1.6	1.5	2.4	0.86	1.4
49.7	0.8	0.67	1.8	0.44	1.2

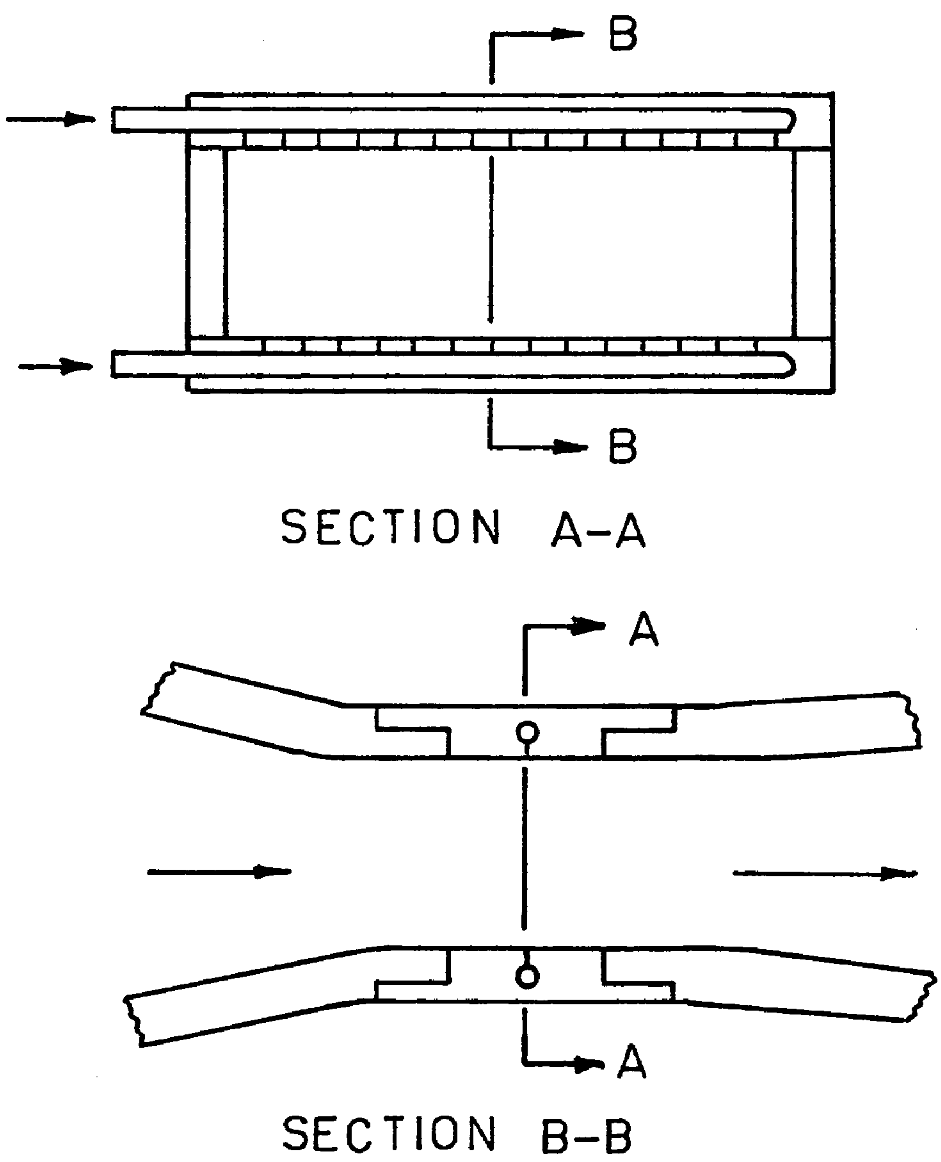

FIGURE 1 SECTIONS THROUGH THE VENTURI SCRUBBER THROAT (SCHEMATIC)

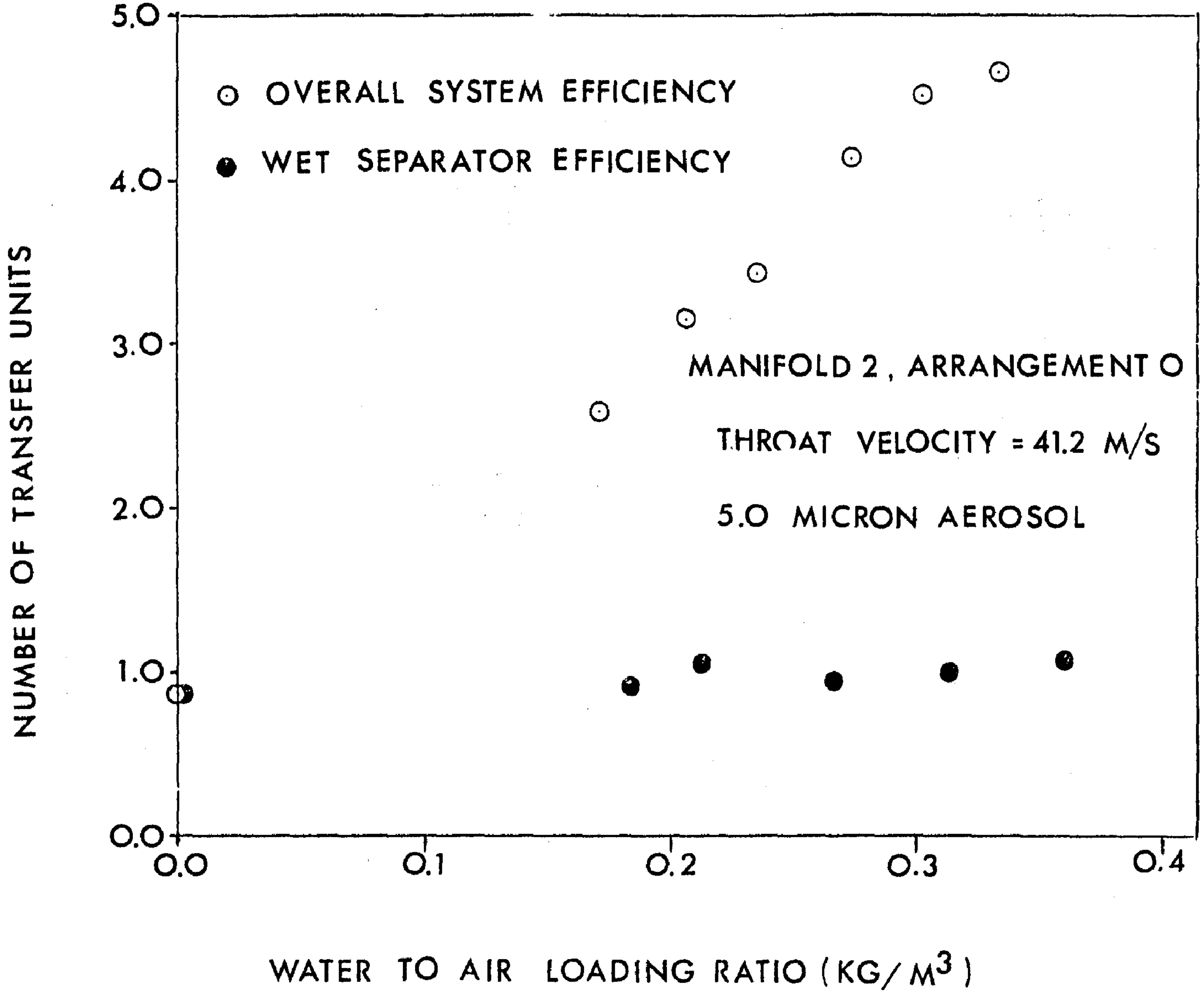

FIGURE 2 TYPICAL EXPERIMENTAL SCRUBBER EFFICIENCY RESULTS

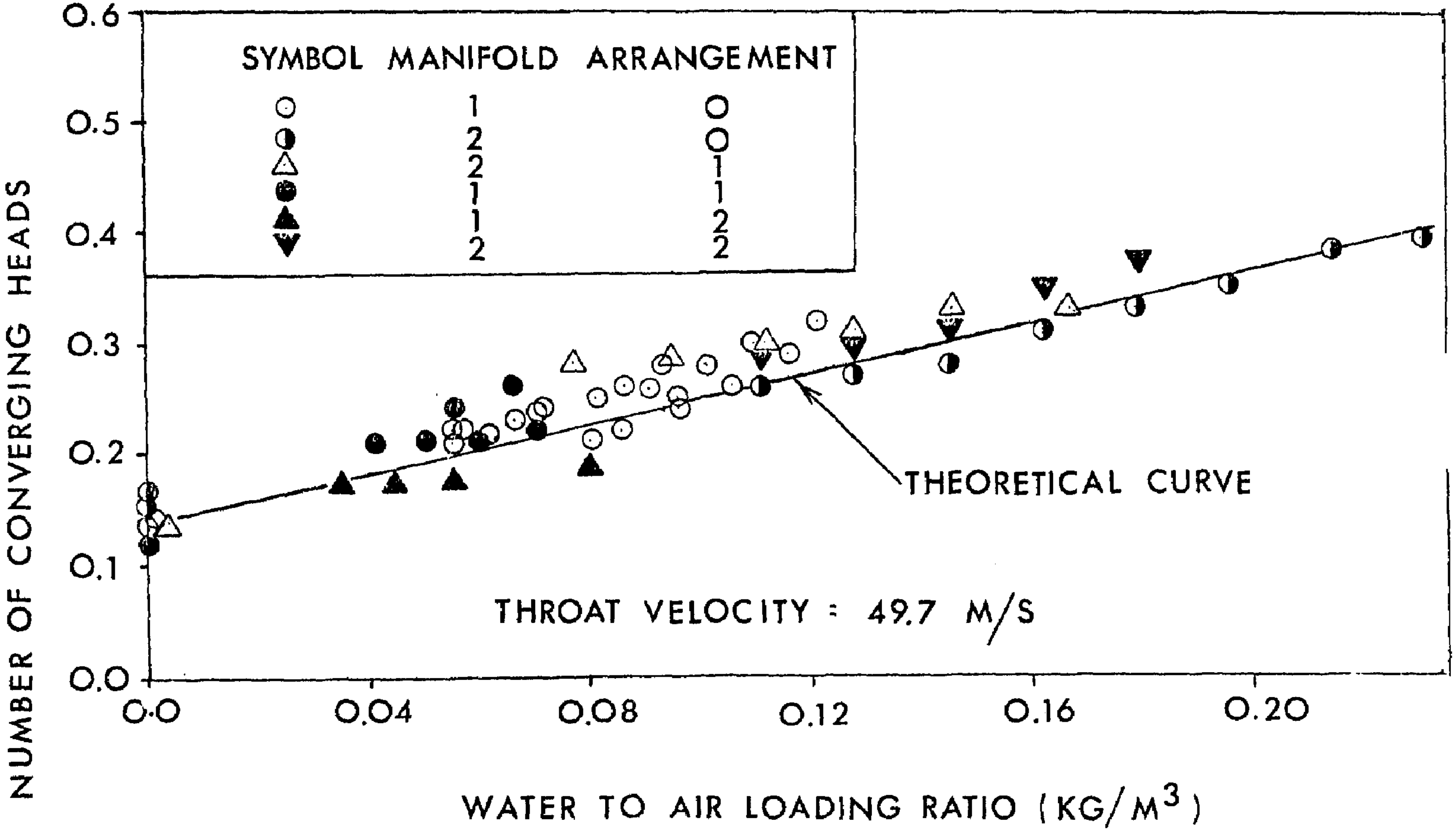

FIGURE 3 PRESSURE LOSS ACROSS THE SCRUBBER AS A FUNCTION OF WATER LOADING AT 49.7 m/sec THROAT VELOCITY

FINE PARTICULATE REMOVAL AND SO_2 ABSORPTION WITH A TWO-STAGE WET SCRUBBER

by

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ABSTRACT

This paper includes results from pilot plant studies and early field demonstration units and a discussion of the application of the limestone wet scrubbing process on a low sulfur sub-bituminous coal. This latter application required the development of a hybrid two-stage scrubber to enable collection of the fine particulate matter as well as removal of a significant amount of the sulfur dioxide.

FINE PARTICULATE REMOVAL AND SO_2 ABSORPTION WITH A TWO-STAGE WET SCRUBBER

by

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INTRODUCTION

In 1965 Combustion Engineering, Inc. initiated studies of limestone wet-scrubbing of SO_2 from utility boiler flue gas and the simultaneous wet removal of fly ash.(1)

This paper will deal specifically with that part of C-E's wet scrubbing development program pertaining to the collection of fly ash. Included are results from pilot plant studies and early field demonstration units constructed in 1968; a review of the measurement techniques employed by C-E in obtaining the mass dust loadings and particulate matter sizing information; and a discussion of the application of the limestone wet scrubbing process on a low sulfur sub-bituminous coal. This latter application required the development of the fine particulate matter as well as removal of a significant amount of the sulfur dioxide. These particulate and SO_2 removal systems are called Air Quality Control Systems (AQCS) at C-E.

BACKGROUND

Wet scrubbers had also been used as dust collectors in many industrial applications. Unfortunately, most of the experiences involved trial and error investigation with little engineering design. These early experiences were hampered by the general lack of good measuring techniques which caused "judgment" to be the major design tool of the wet scrubber industry.

Combustion Engineering's initial survey indicated there were twenty-six manufacturers of commercially available wet scrubbers. Based on a review of literature and contacts with manufacturers, we established our criteria for a wet scrubber as follows:

A. 99% particulate collection
B. 90% or better SO_2 removal
C. Low pressure drop (six inches or less)
D. A liquid to gas ratio of approximately ten gallons per thousand acfm.
E. Low plugging potential

In light of the research and development program we have conducted during the last eight years, we have come to reevaluate these initial criteria. Several have proven unattainable, and most have been determined to be oversimplified. Establishing design criteria today requires significantly more quantification of the process variables and the desired function of the overall process.

The types of scrubbers that C-E studied included four general categories: (a) impingement, (b) spray tower, (c) venturi, and (d) marble bed. After a nine month study conducted in 1965, it was concluded that the marble bed scrubber offered the best overall performance relative to the design criteria.

FIELD DEMONSTRATION UNITS

C-E's early pilot plant efforts led to the building of the first full-size limestone wet scrubbing demonstration units at Kansas Power and Light Co. Lawrence 4 and Union Electric Co. Meramec Station 2.[2,3,4]

Emissions tests conducted on these units between 1969 and 1972 demonstrated their capability of removing 98.5 to 99% of the dust entering the scrubber system. Actual dust loadings on the inlet to the scrubber varied between 4.5 and 6.3 gr/SCF while the outlet dust loading measured in the range of 0.05 - 0.07 gr/SCF.

Particulate sizing measurements were made using the Bahco technique. Table IA displays representative data from the Kansas Power and Light Co. Lawrence 4 unit. These measurements were considered valid since no accurate means of determining size distribution below one micron were available. Additional dust samples taken with a calibrated cyclone indicated that the scrubber was removing approximately 50% of particulate matter one micron or less in size.

Chemical analyses of the outlet dust loadings further revealed that approximately 50% of the material being emitted from the unit was calcium sulfate. This was interpreted to mean either that finely calcined limestone was reacting with sulfur trioxide in the boiler and passing through the scrubber without being wetted, or that a significant amount of liquid carryover through the mist eliminator was occurring. This carryover was at or near saturation with calcium sulfate and therefore could produce solid calcium sulfate particulate matter after the liquid portion was evaporated in the stack gas reheater.

Both explanations gave us reason to believe that future non-furnace injection systems with more efficient mist eliminator components would produce lower particulate matter emission rates. Further, the particulate matter sizing data obtained at Kansas Power and Light Co. indicated good removal of fine dust particles (i.e., 2 microns or less).

PILOT PROGRAM

A pilot plant test program was conducted to establish the system requirements for a wet scrubbing system to remove 99% of the fly ash from the low-sulfur western coal and lower the SO_2 emission levels to a point acceptable to state and federal regulatory agencies. The results of this test program conducted in the summer of 1970 were quite encouraging:[5]

A. A single marble bed scrubber was able to produce an outlet particulate matter emission of 0.03 gr/SCF (Inlet loading equaled 2.0 - 3.0 gr/SCF).

B. A two-stage marble bed scrubber was able to further reduce the dust loading to 0.02 gr/SCF.

At about the same time, C-E entered into negotiations with a midwestern utility to supply a wet scrubber system for a new 700-Mw unit of C-E design which would burn low-sulfur sub-bituminous western coal. Utilizing the information developed from our pilot plant work on low-sulfur western coal and the particulate matter emission data obtained on full size operating systems, C-E entered into a contract to supply a system which would remove 50% of the SO_2 and 99% of the particulate matter to achieve emission levels of 200 ppm SO_2 and 0.04 gr/SCF of particulate matter.[6] A new pilot program tailored to this project was completed in 1971 with the system design illustrated in Fig. 1.

As the next step in the program to develop a successful system, it was decided by the customer and Combustion Engineering to erect a large prototype test facility to test the system parameters, verify system operation, and train operating personnel.[7] A significant amount of experimental work was also required to quantify particulate matter collection and sizing. This effort is discussed in a separate section of the paper.

FIELD PROTOTYPE TESTING

In 1973, C-E and the utility conducted a joint ten month test program of the prototype marble bed assembly system on a unit burning sub-bituminous western coal.[8] It was determined that the original system could not produce an outlet particulate loading required by the regulatory agency of 0.04 gr/SCF. Initial test work showed outlet particulate loadings to be 0.07 to

0.08 gr/SCF. Inlet dust loadings averaged 2.0 gr/SCF. A slip-stream of flue gas was taken from the air heater outlet duct in an isokinetic manner at a rate of 12,000 CFM @ 135 F (design). Analysis of the coal ash, at the AQCS inlet, revealed a typical proportion of fines coming to the system. Fines are defined in this case as particles below two microns in size.

Comparison of particle size distribution (Table IA) as determined by a Bahco centrifugal classifier showed that the midwestern and western coals had comparable size distribution, despite variation in collection efficiency of the wet scrubber. At this point, an in-stack inertial impactor was used to obtain a size distribution of the ash. The results (Table IB) showed that nearly 85% of the particulate matter with a size less than 1.5 microns was actually 0.3 microns or less. This significant amount of "superfine" particulate matter required a major revision in the scrubber system to meet the particulate emission level of 0.04 gr/SCF.

Concurrent with the field prototype operation, Combustion Engineering was pursuing the development of other types of scrubber internals. One of these projects had led to the conclusion that a gas atomizing scrubber in which slurry atomized into droplets by the gas stream and accelerated to high velocity between parallel rows of rods could be coupled with a marble bed scrubber in series to form a two-stage system. A decision was made to revise the field prototype system to include a first stage scrubber.

DESIGNING OF FIRST STAGE SCRUBBER

The basic objectives in the design of the first stage were as follows:

1. To develop a high energy device (gas side) which would insure intimate contact between gas-borne particulate matter and scrubbing liquid so that fines would agglomerate and be removed in the marble bed scrubber.

2. Utilize the same 10% alkaline slurry scrubbing liquid in both the first stage scrubber and the marble bed scrubber.
3. Provide relatively constant removal efficiencies over a wide range of load variations.
4. Develop a geometry that would demonstrate trouble-free operation for the following considerations;
   a. Minimize and control wet/dry interface.
   b. Select materials of construction for a corrosive/erosive environment.
   c. Develop pluggage free nozzles.
   d. Insure deposit free scrubber internal surfaces.

A first stage scrubber was developed after initial laboratory testing on a 1200-cfm pilot plant and subsequent operation of a 12,000-cfm prototype in the field under actual conditions. We have logged over 5000 hours of operation with a first stage scrubber in service and results from an operational as well as performance standpoint exceeded our expectations.

Figure 1 shows how the first stage is coupled to the system. Gas comes to the first stage from the air heater at approximately 350 F. An inlet gas nozzle extends into the expansion chamber. Above this point a steam soot blower is located. This blower is actuated periodically and sweeps the entire inlet nozzle while moving the entire length of the scrubber. The gas expands into the chamber where it is irrigated with slurry.

TWO-STAGE TESTING

Operation of the field prototype as a two-stage system has proceeded for six months. In this mode the gas atomizing scrubber was followed by a marble bed scrubber. The system was evaluated in terms of ΔP requirements to meet guarantee emission rates of SO_2 as well as particulate matter. Materials of construction, design features and liquid requirements were studied on the first stage. In summary, we found that a dust loading of less than 0.04 gr/SCF on the outlet could be obtained continuously with a system ΔP of 13.5 inches and a total L/G of 25.

This was later verified in a thirty day continuous run to demonstrate overall system availability and performance. Subsequently, the system was modified by removing the marble bed and the first stage was operated alone as the SO_2 and dust contactor. This was done in order to determine performance criteria of the gas atomizing scrubber alone. The variables studied were L/G and ΔP while maintaining gas flow and boiler load conditions constant. The circulating liquid to the system was 10% slurry, the solids in the liquid being fly ash and sulfur salts.

During these periods of operation, system availability from the AQCS standpoint was 99%. Routine equipment maintenance was the only reason for short duration shutdowns. Sulfur dioxide removal during these tests varied from 55 to 75%.

Aside from the major consideration of determining the required energy necessary to accomplish removal of the "superfines", we also established the following: Liquid feed to the first stage was needed in quantities exceeding the amount necessary for dust collection to keep the system deposit free. Specially designed nozzles, uniquely located, were required to operate the first stage scrubber.

Performance data obtained with the first stage and marble bed scrubber is illustrated in Fig. 2. The curve shows system ΔP as a function of outlet dust emissions. It can be seen that with at least a 10-inch ΔP across the first stage and the marble bed, the required 0.04 gr/SCF was obtained. Figure 3 shows performance of the first stage scrubber alone. To obtain the required emission an 8-inch ΔP across the first stage was necessary at high L/G, while at low L/G a 10-inch ΔP was required.

PARTICULATE MATTER SAMPLING

A number of forms of sampling equipment have been developed to meet specific requirements in sampling particulate matter emissions from various processes. Stack sampling systems generally consist of sampling nozzle, a probe, a particle collector, a condenser to remove excess moisture, a flow measuring device, a gas exhauster or pump, a temperature measuring device and a device for regulating gas flow.

Both in-stack and external samplers have been used during C-E investigations. For sampling the inlet to the scrubbing system either the BCURA cyclone-filter probe[9] or the ASME alundum filter in-stack systems have been employed. Outlet samples have been obtained utilizing the EPA external cyclone-filter set[10] or the ASME system.

In-stack inertial impactors are extremely valuable in determining particle size information at the emission source. The Mark III University of Washington Source Test Cascade impactor consists of seven impaction stages followed by a filter. The Casella cascade impactor consists of a system of four air jets impinging, in series, on glass discs[11]. In the laboratory the centrifugal classifier (Bahco) has classically been used for determination of terminal velocity distribution of particles.

CONTINUOUS MONITORING OF PARTICULATE EMISSION

In conjunction with manual emission tests performed at a field prototype test facility, C-E also tested a commercial opacity meter in order to determine the meter's usefulness as a continuous monitor of solid particulate emission of AQCS stack gases. As shown in Fig. 4, the meter's output in terms of optical density correlated well with the EPA method of source testing. The meter's accuracy was ± 4% of full scale for a 95% confidence limit. Equally important, the instrument's sensitivity was high enough to reflect changes in the liquid to gas ratio (L/G) and changes in the differential pressure (ΔP) of the rod scrubber.

Basically, the meter consists of a light source and photocell mounted on one side of the stack with a reflector mounted diametrically opposed.[12] The light beam emitted by the source traverses the stack twice. Dust loading, or particulate density is measured by measuring the attenuation of the light beam as it traverses the stack. Since attenuation is directly proportional to optical density, optical density is linearly related to dust loading, assuming a fixed particle size distribution and path length. As possible future application, this instrument could be used to control the pressure drop required in the two-stage scrubbing system concept.

CONCLUSIONS

Based upon data obtained on our prototype unit handling 12,000 CFM of gas with an inlet dust loading averaging 2.0 gr/SCF and a particle size distribution showing a substantial amount of fines (smaller than 1.5 microns), the marble bed scrubber at design pressure drops and L/G could only collect 96.10% of the total dust. With the addition of a first stage collection device, namely a gas atomizing type collector, overall removal efficiency was increased to as high as 99.20%. At this time Combustion Engineering is not prepared to classify this specific sub-bituminous western coal as typical; however, this case represents a specific application of the wet scrubbing system and demonstrates how C-E has designed hardware to handle the particular problems of this application.

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INLET DUST SAMPLES

PARTICLE SIZE ANALYSIS

TABLE IA BAHCO ANALYSIS

Western Sub-bituminous Fly Ash

Micron Size	% Collection
+29	22.5
+13.4	18.4
+ 5.4	29.5
+ 2.6	16.9
+ 1.65	7.2
+ 0	5.5

Midwestern Bituminous Fly Ash

Micron Size	% Collection
+27	18.7
+15.5	13.6
+ 6.2	32.3
+ 3.0	21.2
+ 1.9	7.5
+ 0	6.7

TABLE IB - FLY ASH FROM SUB-BITUMINOUS WESTERN COAL

Field Samples
Impactor

Micron Size	% Collection	
+25	10	
+11	41.2	
+ 5	24.2	
+ 2	13.7	
+1.3	6.4	
+0.55	0.56	4.50
+0.31	1.2	
-0.3	2.74	

BCURA Sample Analyzed By
Bahco

Micron Size	% Collection
+29	16.3
+12	18.7
+ 4.8	31.6
+ 2.3	21.2
+ 1.45	7.3
+ 0	4.9

FIG. 1: MODIFIED TEST FLOW DIAGRAM

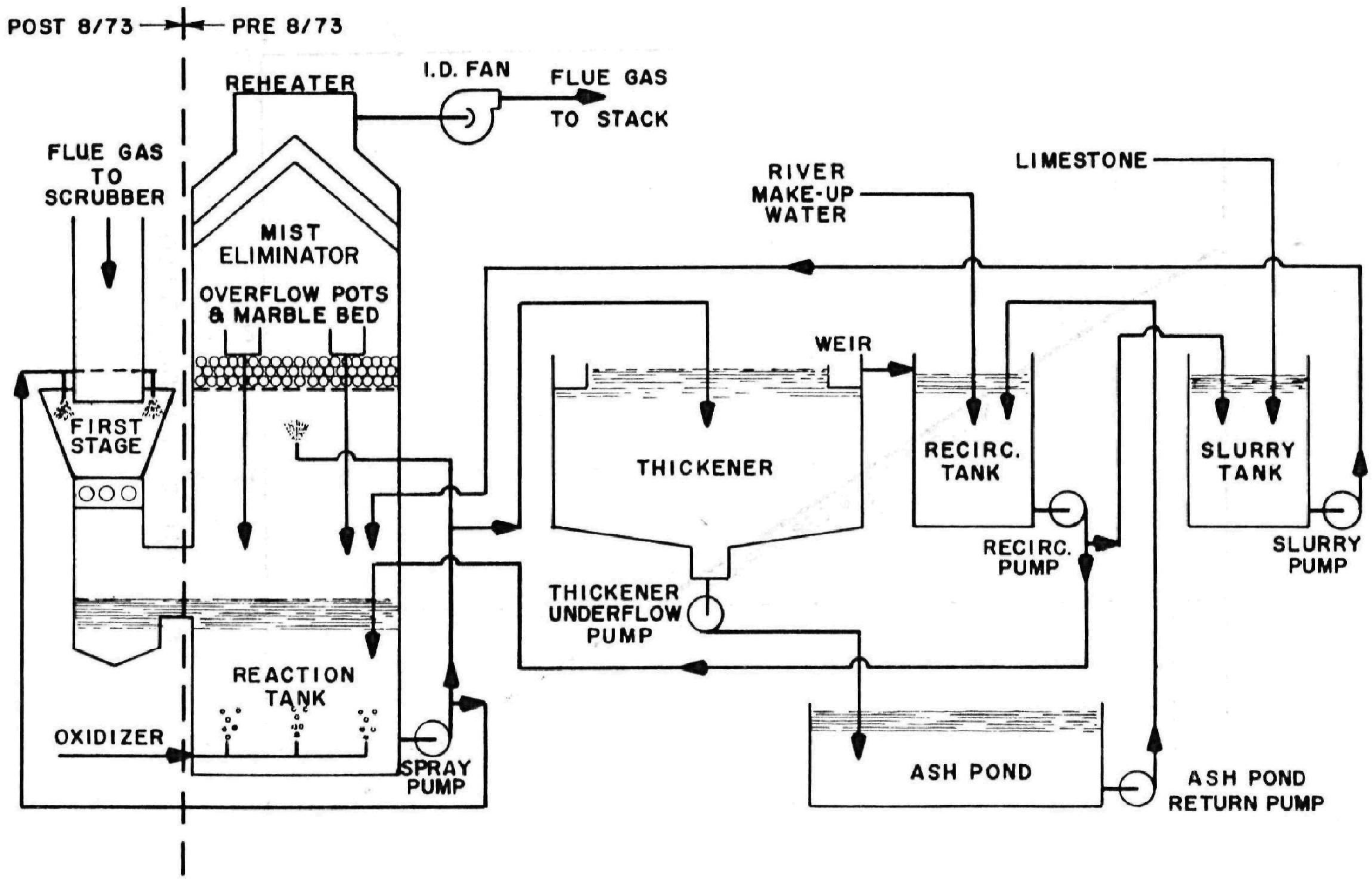


FIG. 2: FIRST STAGE AND MARBLE BED SCRUBBER PERFORMANCE CURVE

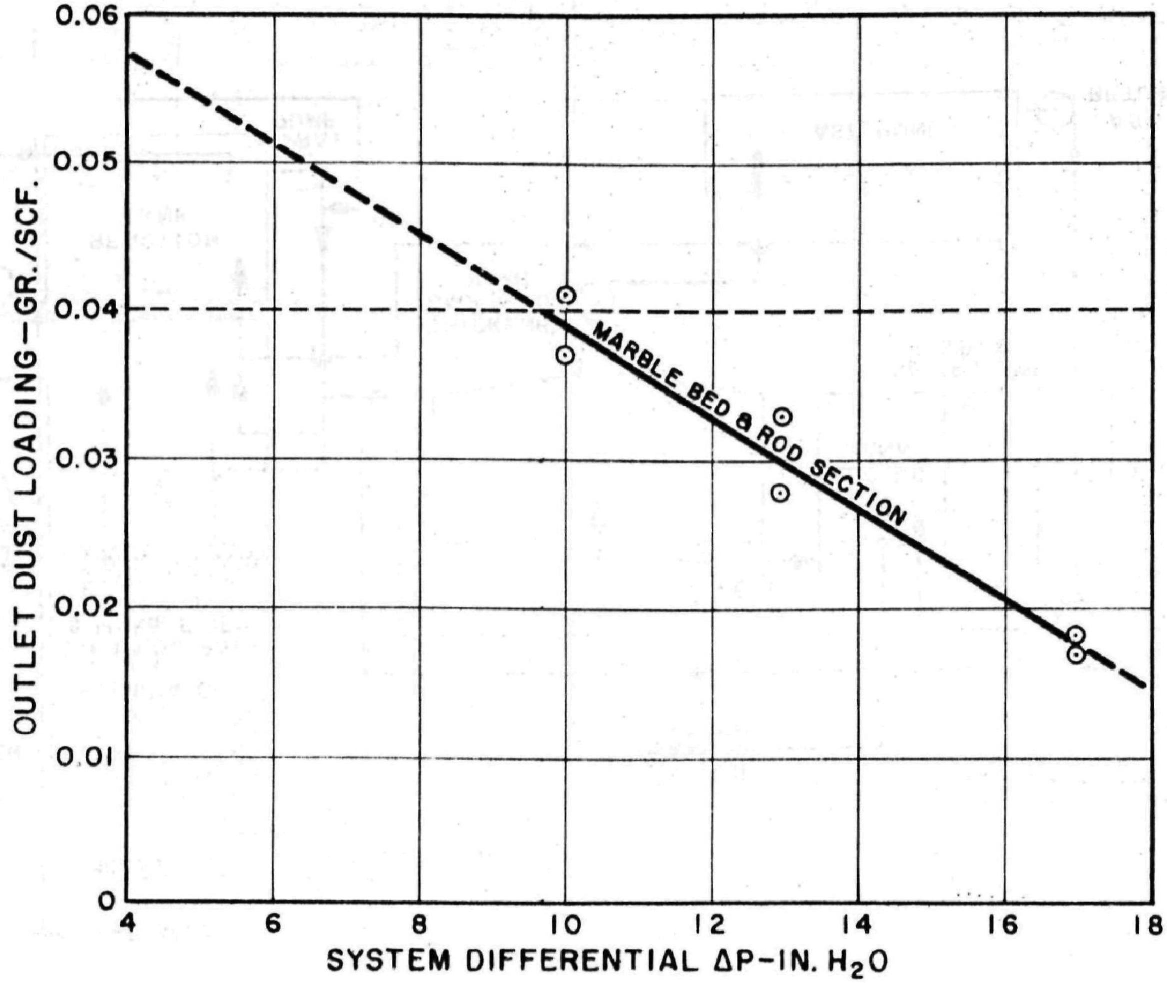
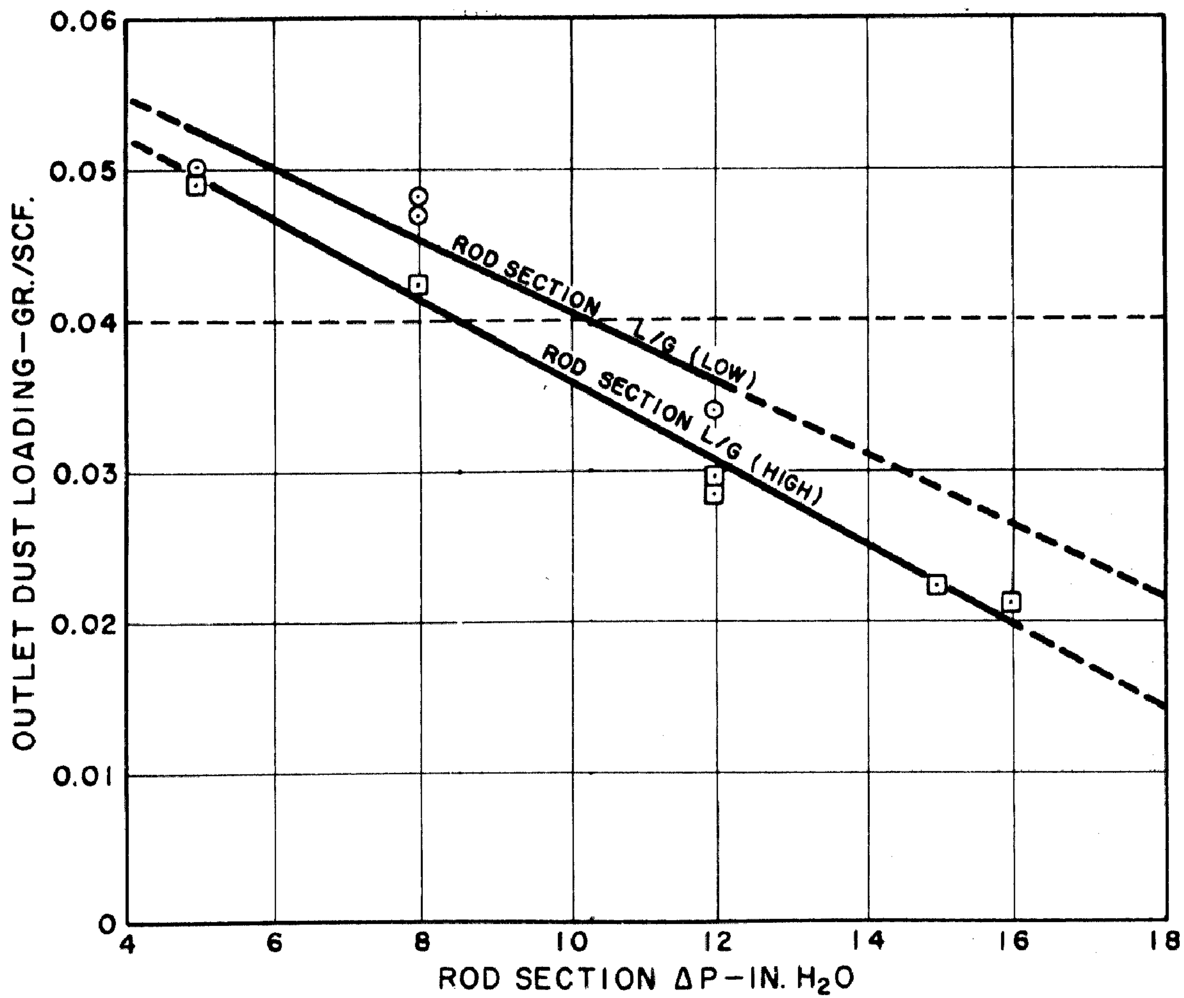


FIG. 3: FIRST STAGE PERFORMANCE CURVE



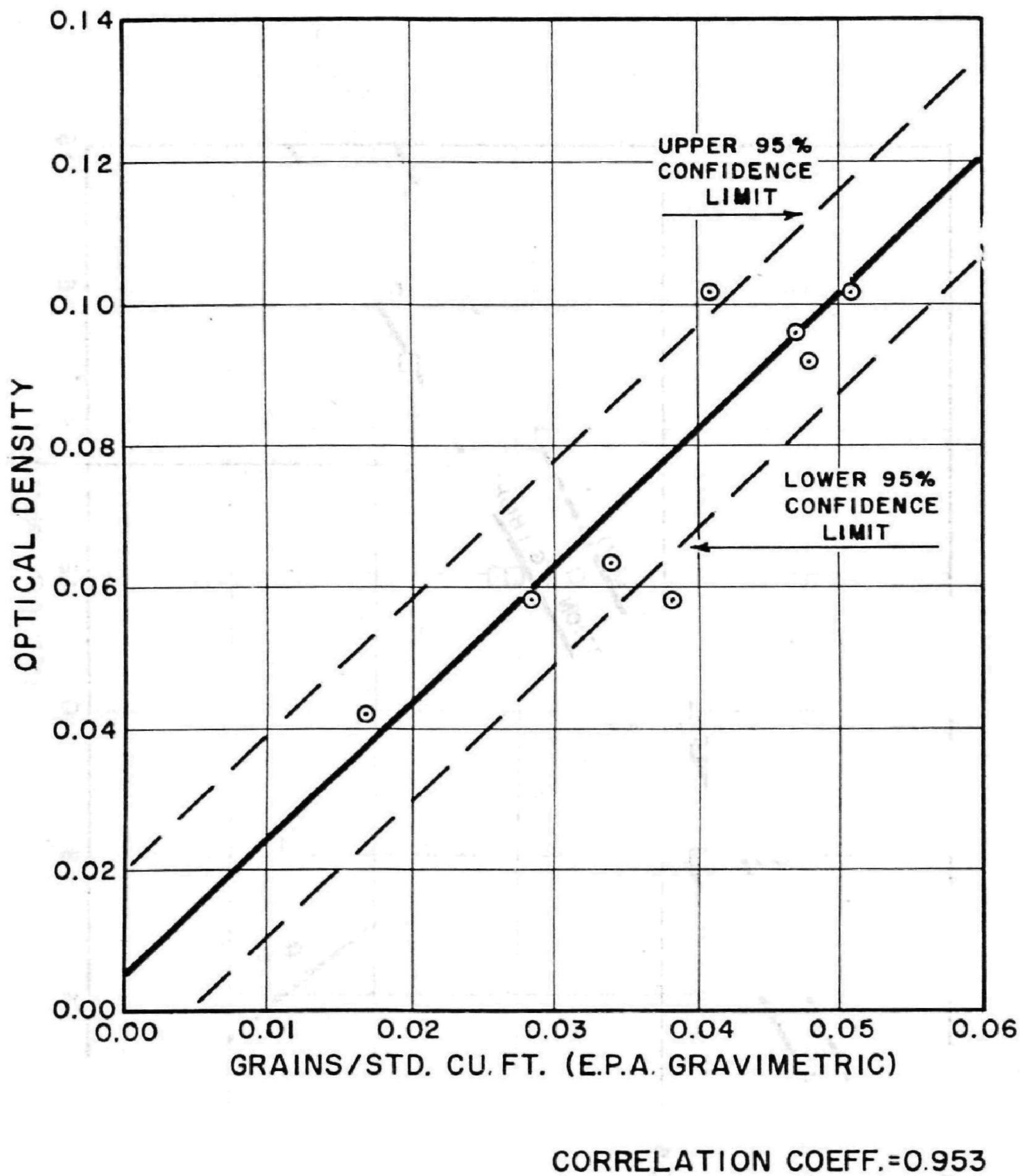


FIG. 4: CORRELATION OF OPTICAL DENSITY AS A FUNCTION OF GRAIN LOADING.

"FLUX FORCE/CONDENSATION SCRUBBING"

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ABSTRACT

Considerations for the engineering design of flux force/condensation (FF/C) scrubbers are reviewed. Fine particulate removal in multiple sieve plate FF/C scrubbers is predicted, using mathematical design models. Results of experimental studies of two multiple sieve plate scrubbers for the removal of submicron particles are given. The published experimental data on FF/C scrubber performance are summarized. A preliminary analyses of the economics of FF/C scrubbers, as compared to the conventional high energy scrubbers, define the most favorable operating conditions for the application of FF/C scrubbers.

"Flux Force/Condensation Scrubbing"

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Wet scrubbers are widely used for the control of air pollution mainly because of their low initial cost and their ability to remove particulate as well as gaseous contaminants. A major drawback of present day scrubbers is the large energy expenditure required to achieve high removal efficiencies for fine particles in the size range of 0.1 to 2 microns (μm) in diameter. This is due to the decreased effectiveness of the inertial and diffusional collection mechanisms for particles in this size range.

Flux force and vapor condensation effects have the potential to cause high removal efficiencies for fine particles in low energy scrubbers. These effects can result from the cooling of a hot, humid gas by contact with cold liquid, the condensation of injected steam, or other means.

Flux force effects on particles have been known for many years and the background is reviewed and discussed in depth by authors such as Waldmann and Schmitt (1966), Goldsmith and May (1966), Hidy and Brock (1970) and Calvert et al. (1972). The present discussion is limited to thermophoresis and diffusiophoresis (which we define to include both diffusiophoretic and Stefan flow forces). Accordingly, we consider only those FF/C scrubbers where particle removal from the gas is aided by a temperature gradient, a vapor concentration gradient, vapor condensation, particle growth due to vapor condensation or combinations of the four.

The work reported in this paper includes both theoretical and experimental studies. Engineering design considerations for FF/C scrubbers are reviewed and the mathematical model for a plate scrubber developed by Calvert et al. (1973) is extended to predict performance of multistage sieve plate FF/C scrubbers. Experimental studies of a bench scale three plate FF/C scrubber and a pilot scale five plate FF/C scrubber are reported. Results of the bench scale study are compared with theoretical predictions made with mathematical design models. A summary of available experimental data on FF/C scrubbing is presented. Economics of FF/C scrubbing is analyzed and compared with the conventional high energy venturi scrubbers on the basis of equivalent performance for fine particulate removal.

FF/C SCRUBBER DESIGN

ENGINEERING DESIGN CONSIDERATIONS

Theoretical and experimentally derived design analyses for FF/C scrubbing have been presented by several investigators, such as Rozen and Kostin (1967), Sparks and Pilat (1970) and Davis and Truitt (1972). An extensive study of design procedures was recently reported by Calvert et al. (1973). They used the unit mechanism approach to develop design equations for spray, sieve plate, impinging jet, wetted wall column and packed bed scrubbers for the removal of fine particles.

The relevant deposition velocities are those due to the flux forces, inertial, gravitational and Brownian diffusional effects. Since the flux force deposition velocities are functions of the temperature and vapor pressure gradients, the magnitude of these gradients at various distances (or residing times) along the gas path through the scrubber must be determined. To account for particle growth, information on the critical saturation ratio for nucleation is needed and this depends on the particle properties and the vapor composition as a function of distance or time inside the scrubber.

The inertial and gravitational deposition velocities are functions of the particle size and density which in turn change due to any vapor condensation on the particle. Vapor composition depends on heat and mass transfer between gas/particles and gas/liquid, which change in magnitude as the gas proceeds through the scrubber. Because of the rapid changes in conditions and the competition between the particles and the liquid surface for the condensing vapor, any realistic design method must consider the point-to-point conditions.

PREDICTIONS FOR MULTISTAGE SIEVE PLATE SCRUBBER

A mathematical model of an FF/C sieve plate scrubber, developed and experimentally verified by Calvert et al. (1973) was extended to predict the performance of multistage scrubbers during this study. The scrubber performance was predicted for two cases; when particles are wettable so that particle growth occurs, and when particle surface properties prevent particle growth. For both the cases, the bottom plate performance was predicted by using the model of Calvert et al. (1973) and the inlet particle size was assumed to be d_{pa} = 0.75 μmA. The model incorporates the following phenomena:

1. Heat transfer between bubbles and liquid.
2. Heat and mass transfer between bubbles and particles.
3. Particle deposition by:
    - A. Impaction during bubble formation
    - B. Diffusiophoresis
    - C. Thermophoresis
    - D. Centrifugation during bubble rise.

For the case of wettable particles, predictions for the subsequent plates were based on the assumption that no additional particle growth or flux force deposition occurs on these plates. Deposition on these plates was predicted for inertial impaction at the point of bubble formation only. This assumption is valid as most of the vapor condenses out on the bottom plate and the particle growth permits high removal due to inertial impaction on the subsequent plates. The penetrations were calculated from the following equation:

$$Pt = \exp\left(-40\ F^2\ K_p\right) \qquad (1)$$

The predicted penetrations for 1, 2 and 3 plates in series are plotted against q' (g vapor condensed/g dry air) on Figure 1. The penetration is highly dependent on the initial particle concentration, as indicated by the comparison of the solid lines, for $n_i = 10^7$ particles/cm^3 with the broken lines, for $n_i = 2 \times 10^5$ particles/cm^3.

For the case where no particle growth occurs, the prediction was based on the following assumptions:

1. Steam is introduced under each plate so that the gas under each plate is saturated.
2. The penetration on each plate is the same if the amount of steam condensed is the same.

Figure 2 is the plot of predicted penetration versus q' for 1, 2, 3 and 4 identical sieve plates in series. The amount of vapor condensed is the total for the number of plates shown.

From the above predictions we can conclude that:

1. For a single plate scrubber there is little effect of particle concentration or critical saturation ratio.
2. Particle growth leads to better performance in multiplate scrubbers than the no-growth situation.
3. If no growth occurs, better steam utilization results from the introduction of steam under each plate rather than only the bottom plate.

EXPERIMENTAL

An experimental study of a single sieve plate FF/C scrubber was reported by Calvert et al. (1973). This research showed that diffusiophoresis was the major collection mechanism for the single plate scrubber. Particle growth by condensation could not be utilized significantly on a single plate as the conditions for removing grown particles by impaction did not exist on the plate. The purpose of the present investigation was to determine the FF/C scrubber performance at higher q' values and provide conditions for collecting grown particles by impaction by using a multistage scrubber.

BENCH SCALE FF/C SCRUBBER

APPARATUS

A schematic flow diagram of the experimental apparatus is shown in Figure 3. The major components were a three sieve plate FF/C scrubber and the aerosol generator. The sieve plates were made from 1.6 mm aluminum sheet with the overall diameter of 10.2 cm. Each plate had 60 perforations of 3.2 mm (1/8") diameter, adding up to 5.9% free area on the plate. On each plate the flow was radially inward to a central downcomer, 2.54 cm in diameter.

Aerosol was produced by dispersing reagent grade iron oxide (Fe_2O_3) powder from an aqueous suspension. Freshly prepared aqueous suspension of 4% Fe_2O_3 and 0.05% $Na_4P_2O_7 \cdot 10\ H_2O$ was used for each experimental run. The sodium pyrophosphate was added to the suspension as a dispersing agent. The suspension was continuously stirred during the run to further prevent settling. The suspension was dispersed by a compressed air atomizer. The aerosol was dried by heating and then passing it over concentrated sulfuric acid. An impactor with a cut diameter of approximately 2 μm removed the larger particles from the aerosol stream.

EXPERIMENTAL PROCEDURE

The experiment was started by adjusting the water, aerosol generator and ambient air flow rates to the desired values. After attaining steady foams on the sieve plates, heat and filtered steam were added to the air stream to attain the desired values of temperature and humidity. After a steady state was reached, which took from thirty to sixty minutes, the particulate sampling was started. The experimental conditions were very stable once the steady state was reached. For all the experimental runs reported, the inlet gas temperature varied within $\pm 0.5°C$ during the experimental period.

Two heated sample probes were located in the scrubber inlet and outlet gas pipes, respectively. A third heated probe was located above the bottom plate inside the scrubber. The particulate size distributions were measured with an eight stage non-viable Andersen Sampler. The sampler was placed in a temperature controlled oven and was followed by a Gelman type "E" glass fiber filter to capture particles penetrating the bottom stage of the impactor. The size distributions were determined gravimetrically. Particle loadings in the scrubber inlet and outlet gas streams were measured gravimetrically with Gelman type "E" glass fiber filters placed in the oven. The samples were pulled simultaneously from the two gas streams. The sampling period was one hour and the samples weighing less than 2.5 mg were discarded.

RESULTS AND DISCUSSIONS

Operating conditions and performance of the three sieve plate column are shown in Table 1. The dry air and water flow rates remained constant for all experimental runs. The performance of the column was studied for different gas inlet temperatures. The inlet gas was maintained saturated with water vapor and the scrubber performance was measured for a wide range of q' values, from 0.07 to 0.53 (g vapor condensed/g dry air). During the experimental runs, the particle size distribution was found to be log-normally distributed in the following range:

$$d_{pg} = 0.75 \pm 0.11 \ \mu mA; \ \sigma_g = 1.61 \pm 0.22$$

Overall penetration values for the experimental runs are plotted against q (g vapor condensed/g particles in) on Figure 4 and against q' (g vapor condensed/g dry air) on Figure 5. For comparison, the performance of only the bottom plate of the three plate column is also plotted on these figures. The results verified the following predictions from the mathematical model described earlier:

1. For the same amount of vapor condensed in the scrubber, the three plate column gives lower penetrations compared to a single plate column. Note that most of the condensation occurred on the bottom plate of the scrubber. Thus, higher performance of the three plate column can be attributed to the particle growth effect.
2. A single plate does not give high efficiencies even when the amount of vapor condensed is high. The major contribution of the bottom plate is to provide for particle growth during bubble rise on the plate. Thus, the bottom plate may be designed so as to minimize the pressure drop.

During the experimental runs the foam density, F, was measured to be 0.4 when the entering gas was almost dry. The foam density increased to about 0.75 when the entering gas was saturated with water vapor and the foam appearance changed to irregular bubble shapes.

Kotrappa and Wilkinson (1972) report that the density of iron oxide aerosol particles range from 2.2 to 2.6 g/cm^3, when the aerodynamic diameters are in the size range of 0.3 to 3.5 microns. If a particle density of 2.5 g/cm^3 is assumed, the iron oxide particle number concentrations at the scrubber inlet was in the range of 10^5 to 10^6 particles/cm^3 during the experimental runs.

The experimental results are compared with predictions from the mathematical model on Figure 6. Comparison of the single plate performance showed a good agreement up to q'=0.1. For higher values of q', the model predicts a better performance. This is possibly due tc the change in foam characteristics in this range. Experimental results for the three plate scrubber show a higher performance than predicted when no particle growth takes place; and a lower performance than predicted when particles grow. Besides the effect of foam characteristics, the discrepancy is interpreted to indicate the existence of more nuclei than accountable as iron oxide particles.

The results compare better with predictions for 10^7 or more particles/cm^3, indicating that there may have been competing nuclei, other than iron oxide, present in the air stream. These may have been inadvertently introduced with the steam or formed by nucleation of sulfuric acid vapor during the aerosol drying process. The gas temperature as it passed over the concentrated sulfuric acid bath was somewhat less than 90°C. At this temperature the sulfuric acid vapor pressure is 0.12 mm Hg. For a comparable sulfuric acid vapor pressure, Amelin (1967) reported the formation of sulfuric acid nuclei due to homogeneous condensation, in the order of 10^{10} nuclei per cm^3. For the gas resident time in the apparatus, coagulation due to Brownian diffusion would reduce this number concentration to about 10^8 nuclei per cm^3. This would then clearly account for the discrepancy with the predictions from the mathematical model.

PILOT SCALE FF/C SCRUBBER

APPARATUS

The same general set up of experimental apparatus as described for the bench scale studies was used in a pilot scale study. The major components were a five plate FF/C scrubber and the aerosol generator. All the plates were identical and were made from 0.3 m x 0.3 m x 1.6 mm 316 stainless steel sheet. The perforations were 3.2 mm (1/8") in diameter, adding up to 9% free area on the plates.

The aerosol was produced by dry dispersing black iron oxide powder. The powder, after drying, was sieved through 16 mesh screen. It was then fed to the inlet of a high pressure blower through a screwfeeder arrangement. The radial blades of the blower were modified to increase recirculation and shear on the aerosol particles within the blower. A multiple round jets impactor with a cut diameter of 4 μmA was used to remove large particles from the dispersed aerosol. Eight polonium 210 ionizing units were used to neutralize the electrical charges on the particles.

EXPERIMENTAL PROCEDURE

The scrubber operating procedure was the same as described for the three plate bench scale scrubber. Andersen samplers, followed by Gelman type "E" glass fiber filter papers were used to determine the particle size distributions and loadings in the scrubber inlet and outlet gas streams. The outlet sample flow rates were between 2 to 3 times the inlet rates, due to the low $\overline{Pt}$ values. When q' was greater than 0.2, the outlet was sampled for 250 minutes while the inlet was sampled intermittently for the first 10 minutes of the hour, for a total of 50 minutes.

RESULTS AND DISCUSSION

Operating conditions and performance of the five plate column are shown in Table 2. The particle penetrations for these runs, as a function of particle diameter (aerodynamic) are plotted on Figures 7, 8, 9 and 10. The particle penetration, as a function of the condensation ratio, is plotted on Figure 11 for 0.6 μmA and 1.0 μmA particles.

The scrubber performance was far superior to the performance of the bench scale scrubber. Again assuming the particle density of 2.5 g/cm^3, the particle number concentration entering the scrubber ranged from $5x10^5$ to $5x10^6$ $particles/cm^3$, during the experimental runs. These results compare well with the predictions from the mathematical design model for wettable particles; indicating higher penetrations than predicted for $2x10^5$ $particles/cm^3$ and lower penetrations than predicted for 10^7 $particles/cm^3$.

The results clearly indicate the significant effect of condensation ratio, q', on the scrubber performance. The particle penetrations decreased with an increase in q'. Also, the particle penetration decreased with an increase in the inlet particle size.

REVIEW OF FF/C SCRUBBING STUDIES

A summary of the high points of the available data on FF/C scrubbing is presented in Table 3, "FF/C Scrubbing Performance Data Sources" and Figure 12, "Particle Penetration versus Condensation or Injection Ratio". Some noteworthy points shown in Table 3 and Figure 12 are as follows:

1. Particle penetration depends heavily on the amount of water vapor condensed per unit mass of dry gas (q'). The condensation ratio, q', can be shown theoretically to be sufficient to define particle deposition rate, without regard to particle concentration, if there is no condensation on the particles.
2. Particle penetration also depends significantly on particle concentration. By referring to the concentration data given in Table 3, one can see that there is a clear trend of penetration decreasing as particle number concentration decreases. This effect can be shown theoretically to accompany condensation on particles and their growth at the expense of the water vapor concentration in the gas.

Because the particles use some of the steam, there is a lower diffusiophoretic sweep velocity to deposit them. Also, the fewer the particles which share a given quantity of condensation, the larger they will grow and the easier they are to collect.

3. The data for references 5 and 7 are the only ones in Figure 12 for penetration versus steam injection ratio rather than condensation ratio. The exceptionally low penetration shown for soluble materials such as Na_2CO_3 and Na_2SO_4 may be partly due to their being able to grow by condensing water vapor when the relative humidity is less than 100%.

FF/C SCRUBBING COSTS

Costs for FF/C scrubbing are highly dependent on the amount of vapor which is condensed, especially if steam (or the fuel to evaporate water) has to be purchased. In order to provide some general guides as to economically attractive operating conditions, the major operating costs for FF/C scrubbers have been compared to those for high energy scrubbers. Depreciation costs are not included in these comparisons because they will be roughly in the same cost range and they will usually be overshadowed by power and utility costs. Likewise, any costs for waste treatment would be nearly the same.

A base case of 1,420 m^3/minute (50,000 C.F.M.) of dry gas was chosen for illustration. Fan power costs for 200 cm W.C. (80"W.C.), 400 cm W.C., and 500 cm W.C. pressure drop scrubbers were computed for an overall fan and motor efficiency of 50% and power costs of 1¢/KWH. Hourly costs for these conditions are plotted (dashed lines) on Figure 13 a graph of hourly operating cost vs. the condensation ratio. Since no vapor is condensed in the high energy scrubber, the dashed lines are horizontal.

If steam has to be purchased or generated from purchased fuel, it might cost somewhere around \$1.32/MKg (\$0.60/1,000 lb.) One line is shown on Figure 13 for costs due to steam alone. Cooling water will also be required to condense the steam and it will cost anywhere from 0.26¢/MKg (1¢/M gal) to 4¢/MKg (15¢/M gal). We expect that recirculating cooling tower water might be available for around 0.8¢/MKg, based on quoted costs and on cooling tower depreciation plus pumping costs.

The amount of cooling water needed will depend on the temperature rise of the water in the scrubbing system. If one assumes a 29°C (50°F) temperature rise, about 20 g of cooling water will be required to condense 1.0 g of steam. Based on this assumption, the lines for hourly cost due to steam plus cooling water and for cooling water alone (at two prices) were plotted on Figure 13. If one assumes that the FF/C scrubbing system might have an overall pressure drop of 25 cm W.C. (10"W.C.) then the total hourly operating cost for such an FF/C scrubber purchasing water at 0.8¢/MKg, but not paying for steam, would be as shown in Figure 13.

One may make the following observations based on the illustrations in Figure 13.

1. The most favorable set of circumstances will be approximately as shown by the line for 0.8¢/MKg water and 25 cm W.C. fan costs; corresponding to scrubbing a hot gas which does not require any purchased steam. Depending upon the particle penetration required, this system could compete with a wide range of conventional scrubbers. For example, if 58% penetration of non-wettable particles with an aerodynamic diameter, d_{pa}, of 0.5 μmA were required, a conventional venturi scrubber would have to be operated at about 200 cm W.C. pressure drop. Figure 12 shows that FF/C scrubbing would require around 0.05 g vapor condensed/g dry gas. The hourly operating cost ratio for conventional

to FF/C scrubbing would, therefore, be about ($9.50/$2.50), or 3.8 times more expensive than FF/C.

2. Cooling water costs as high as 2.64¢/MKg (10¢/M gal) or even 4¢/MKg (15¢/M gal) can be economically acceptable where low penetration is required.
3. Purchased steam plus cooling water can be economically competitive where low penetration is required. For example, a 400 cm W.C. pressure drop venturi would be required to give 27% penetration @ d_{pa} = 0.5 μmA. Figure 12 shows that a condensation ratio of 0.07 to 0.17 g/g might be required in an FF/C scrubber, depending on the number concentration of particles, their nucleation characteristics, and the scrubber configuration. Inspection of Figure 13 shows that the cost comparison would be close and the final resolution of which system is cheaper would require additional experimental testing and design computation.

CONCLUSIONS

FF/C scrubbers are capable of high collection efficiency on fine particles. Engineering design of FF/C scrubbers is possible with the help of mathematical models when specific details of heat and mass transfer, particle concentration, nucleation of condensation and the mode of gas-liquid contact are available.

The performance of an FF/C scrubber depends heavily on the amount of vapor available for condensation and the number concentration of particles. Diffusiophoresis and inertial impaction enhanced by particle growth are the most significant collection mechanisms in FF/C scrubbers, while thermophoresis has minor effect.

Multiple-stage or continuous contact type of scrubbers are most suitable for FF/C application. They can be readily adapted to provide different conditions and geometry along the gas path to accommodate changing flow rates and particle concentrations.

Distribution of the condensing vapor over several stages is preferable because of the enhanced growth which can occur after the particle concentration has been reduced.

Economic considerations define the most favorable area of application for FF/C scrubbing as those situations in which the enthalpy of vaporization is available from the gas to be cleaned. The purchase of steam can be justified when high collection efficiency on fine particles is needed, or an existing scrubber has to be upgraded for the removal of submicron fume. The FF/C scrubber efficiency is relatively unaffected by particle size. Thus, FF/C scrubbers become comparatively more economical as the particle size of the pollutants decrease.

ACKNOWLEDGEMENT

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NOMENCLATURE

c = particle mass concentration, g particulate/cm^3 gas
d = diameter, cm or μm
d_{pg} = mass mean diameter, μm or μm (g/cm^3)$^{1/2}$
F = foam density, volume fraction
K_p = particle inertial impaction parameter

$$= \frac{d_{pa}^2 \, v_h \times 10^{-8}}{9 \, \mu_G \, d_h}$$

n = particle number concentration, no./cm^3
Pt = penetration (one minus efficiency), fraction or percent
$\overline{Pt}$ = overall penetration
q = vapor condensed per unit mass of inlet particles, mass fraction
q' = condensation ratio, g vapor condensed/g dry gas
r = radius, cm or μm
S = saturation ratio, vapor partial pressure/vapor pressure at the gas temperature
T = temperature, °K or °C
u = deposition velocity, cm/sec
v = velocity, cm/sec
y = gas humidity, g vapor/g dry gas
σ_g = geometric standard deviation
μ = viscosity, g/cm-sec

<u>Subscripts</u>

a = aerodynamic
G = gas
h = plate perforation
i = inlet
L = liquid
o = outlet

<u>Subscripts</u> (continued)

p = particle
pC = particle, centrifugation
pD = particle, diffusiophoresis
pT = particle, thermophoresis

Table 1. THREE PLATE FF/C SCRUBBER; EXPERIMENTAL CONDITIONS AND RESULTS

All plates are identical, 60 perforations of 0.32 cm diameter
Dry air flow rate = 0.4 (m^3/min) @ 21°C, 1 atm.
Inlet water flow rate = 2.54 (liters/min)
Inlet air saturated at T_i

Run No.	Gas Conditions					Water Temperatures			Pressure Drop (cm H_2O)			c$\times 10^9$ (g/cm^3)	Pt_1 (%)	$Pt_2 \times Pt_3$ (%)	$\overline{Pt}$ (%)
	T_i	$T_{1,2}$	$T_{2,3}$	T_o	q'	T_{Li}	$T_{L1,2}$	T_{Lo}	P_1	P_2	P_3				
1	51	33.3	30	27.2	0.07	27	27	31	4.7	4.1	5.1	13.4	81.8	61	49.9
2	51	33.3	30	27.2	0.07	27	27	31	4.7	4.1	5.1	14.0	84.8	59.3	50.3
3	60	38.8	31	28.4	0.13	27	28.7	36.9	4.9	4.4	5.6	15.0	70.6	45.1	31.9
4	60	38.8	31	28.4	0.13	27	28.7	36.9	4.9	4.4	5.6	13.5	76.1	44.4	33.8
5	60	38.8	31	28.4	0.13	27	28.7	36.9	4.9	4.4	5.6	14.4	75.5	49.6	37.4
6	71	--	33	27.8	0.27	26.5	29.5	40	5.0	4.2	5.7	15.8	64.8	40.0	25.9
7	71	--	33	27.8	0.27	26.5	29.5	40	5.0	4.2	5.7	18.1	59.6	34.7	20.7
8	71	--	33	27.8	0.27	26.5	29.5	40	5.0	4.2	5.7	13.2	64.1	34.2	21.8
9	80	58.2	39	29.5	0.5	27.5	35.2	58	---	5.0	6.0	14.8	50.0	33.1	16.6
10	80	58.2	39	29.5	0.5	27.5	35.2	58	---	5.0	6.0	18.2	47.0	36.8	17.3

NOTE: All temperatures in degrees centigrade.
q' = g vapor condensed/g dry air.
c = particle mass concentration
Numbered subscript refer to the plate number, bottom plate is denoted as plate 1. A combination of numbers in a subscript such as (1,2) refer to conditions in between the two plates.

Table 2. PILOT SCALE FF/C SCRUBBER; OPERATING CONDITIONS

Plate configuration - Five identical plates with 3.2 mm round perforations
Free area = 9%; Plate active area = 9.29×10^{-2} m^2

Dust used - Pure black iron oxide, - 16 mesh

Cold water introduced on top plate, flow rate = 0.64 liters/sec.

Run No.	Gas Inlet Conditions: Flow $\left(\frac{dsm^3}{min}\right)$	Gas Inlet Conditions: Temp. (°C)	Gas Inlet Conditions: Moisture (% Vol.)	q' x10	Liquid Temp. (°C): In	Liquid Temp. (°C): Out	Particulate: Load $\times 10^3$ (g/dsm^3): In	Particulate: Load $\times 10^3$ (g/dsm^3): Out	Particulate: d_{pg} In	Particulate: d_{pg} Out	Particulate: σ_g In	Particulate: σ_g Out	Scrubber Press. drop (cm W.C.)
1	5.17	20	1.2	-	18	-	45.1	9.4		Filter	Samples		34.8
2	5.3	25	1.3	-	22	-	43.1	7.1	1.27	0.92	1.8	1.4	32.5
3	5.3	23	1.4	-	-	-	46.3	10.5	1.37	1.06	1.8	1.5	32.8
4	5.14	42	8.2	0.4	19.5	28.0	44.0	7.33	0.79	0.68	2.0	1.5	34.8
5	4.73	43	8.5	0.49	13.8	22.9	28.8	1.63	1.21	0.73	1.7	1.6	32.3
6	4.85	55	16.0	1.04	13.5	33	58.9	0.94	1.12	0.74	1.8	1.6	32.5
7	5.06	60	18.2	1.27	11	42.5	15.7	0.35	0.97	0.8	1.6	1.7	33.8
8	3.08	68.2	27.8	2.32	15.3	45.0	28.1	0.42	1.21	0.6	1.8	1.4	34.2
9	2.83	71.2	33.4	2.81	27	57.5	46.0	0.74	1.16	0.55	1.6	1.4	31.9

NOTE: All flow rates expressed at 0°C, 1 atm.

q' = vapor condensed, g/g dry air

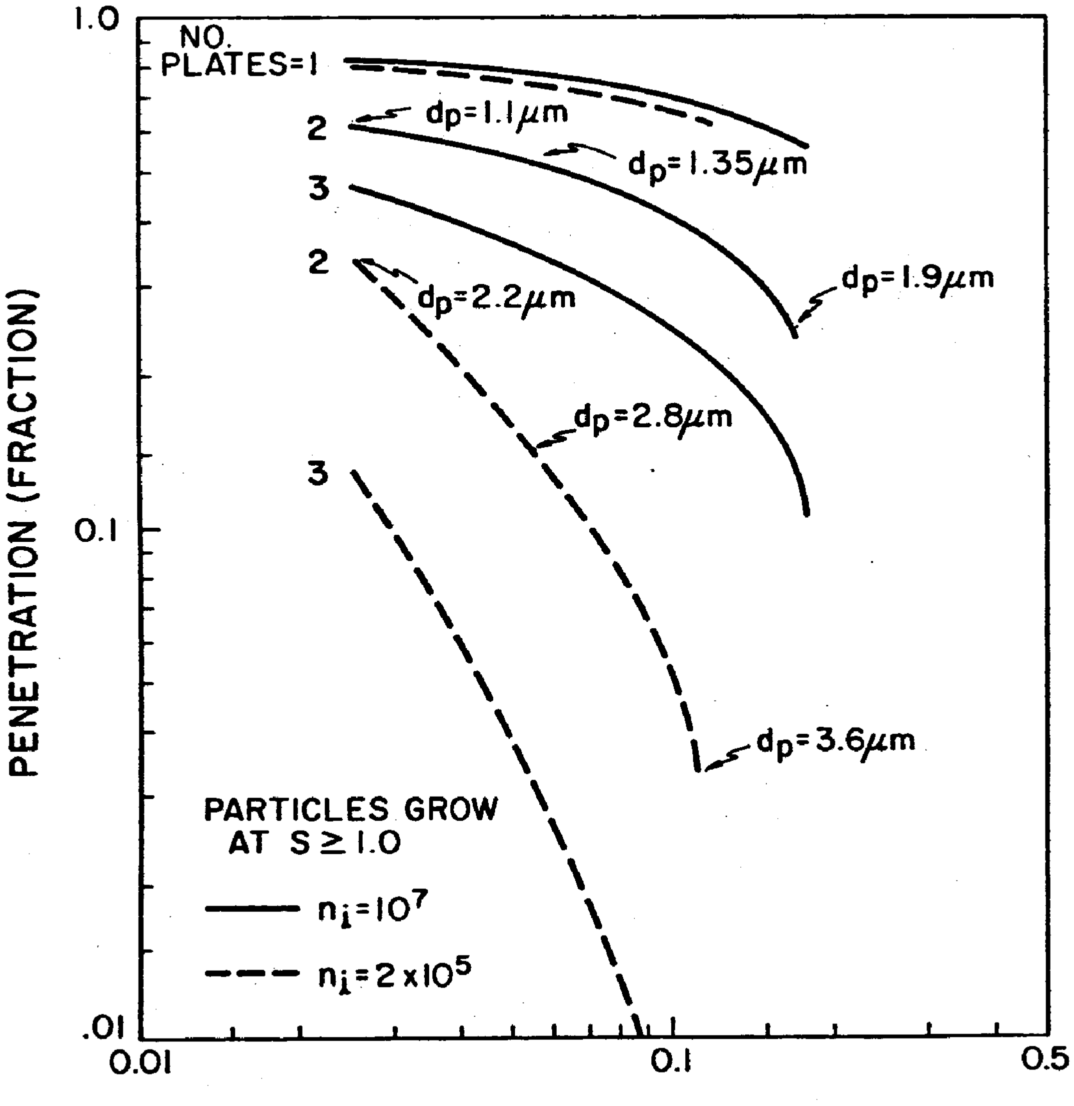
d_{pg} = aerodynamic mass mean diameter, μmA

σ_g = geometric standard deviation.

Table 3. FF/C SCRUBBING PERFORMANCE DATA SOURCES

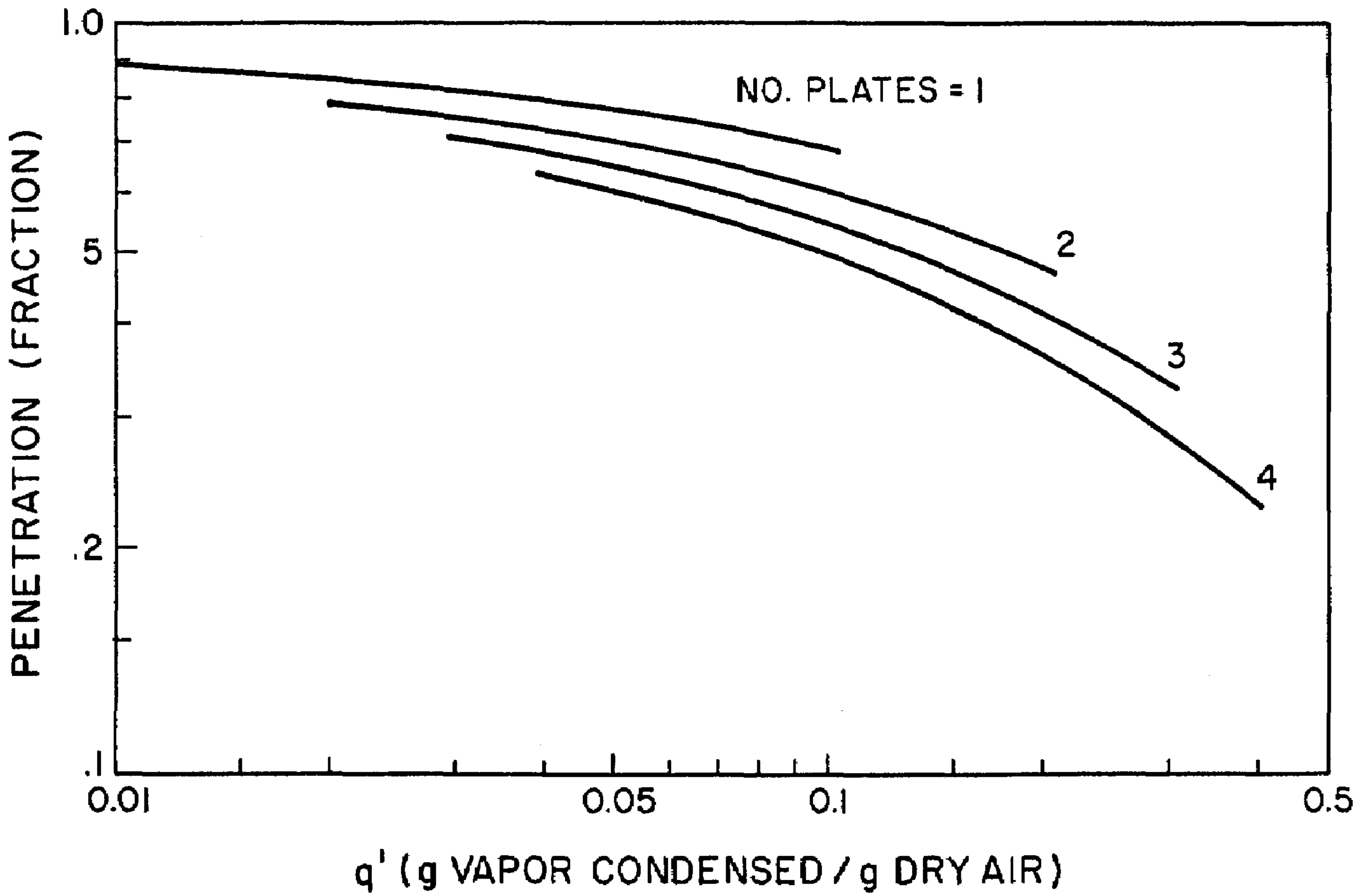
Ref. #	Investigator(s)	Scrubber Type	d_{pg} (μm)	Particle Material	n_p #/cm^3
1	Calvert, Goldshmid, Leith, Jhaveri (1973)	Sieve plate (1 cold plate)	0.7	D.B.P.	5×10^5
2	Calvert, Jhaveri (present investigation)	Sieve plate (3 cold plates)	0.4	Ferric Oxide	10^5-10^6
3	Fahnoe, Lindroos, and Abelson (1951)	(A) Cyclone, or (B) Peabody (1 plate)	< 2.0	NaCl	10^3
4	Goldsmith and May (1966)	Tubular Condenser	?	Nichrome & others	?
5	Lancaster and Strauss (1971)	Steam Nozzle + Spray + Cyclone	1.0	ZnO	10^5 -10^6
6	Litvinov (1967)	Venturi + 2 sieve plates	1.7	Apatite	~10^5
7	Prakash and Murray (1973)	Steam nozzle + Dry Duct		ZnO, $CaCO_3$, Na_2CO_3, Na_2SO_4	
8	Rozen and Kostin (1967)	Sieve plate with alternate hot and cold plates	0.3	Oil	10^5 -10^8
9	Schauer (1952)	Steam nozzle + Peabody(5 plates)	0.3	D.O.P.	2×10^7
10	Stinchombe and Goldsmith (1966)	Tubular Condenser	0.1	Iodine	10^3 -10^4
11	Terebenin and Bykov (1972)	Vertical Wetted Planes	0.05	Tin Fume	5×10^7

Note:
d_{pg} = Mass median diameter, μm
n_p = Number concentration of particles, #/cm^3



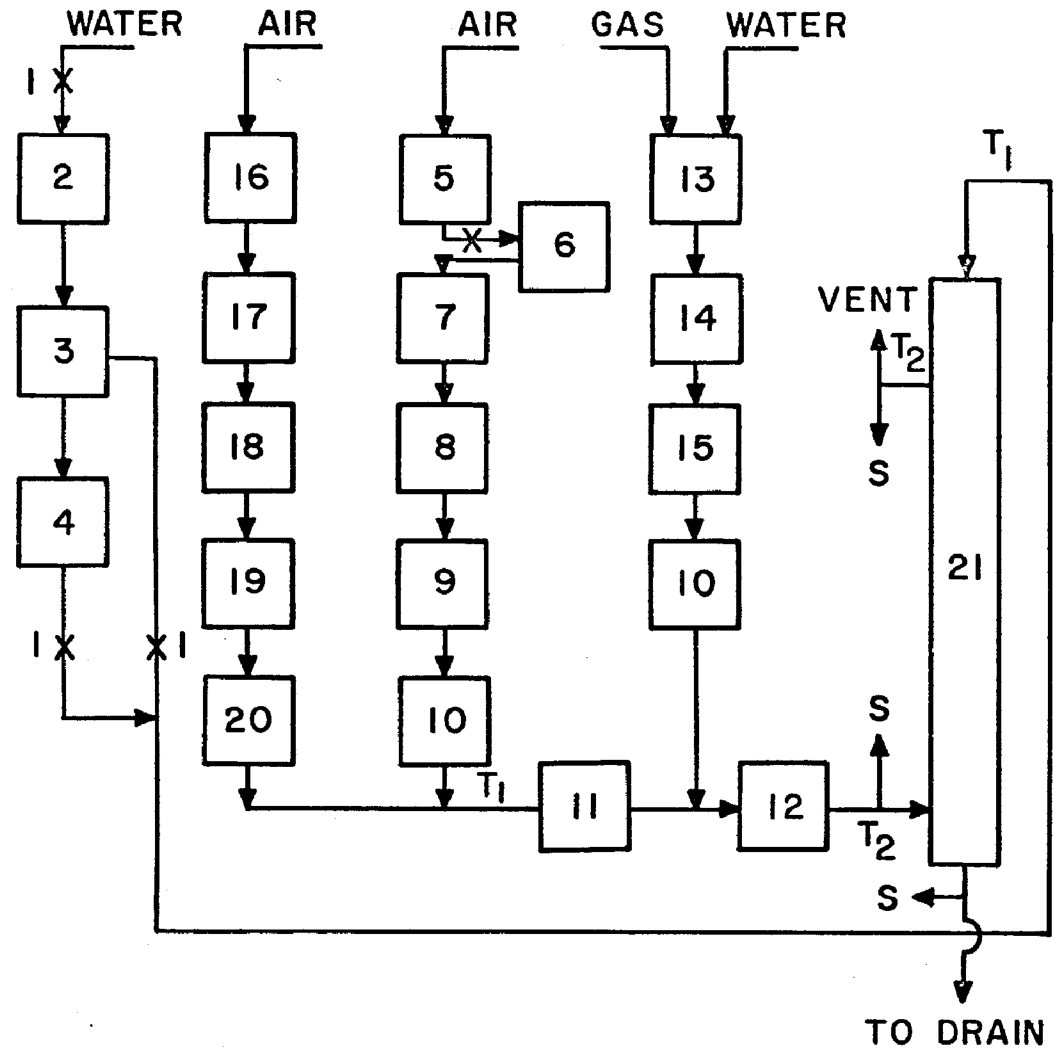
PREDICTED PENETRATION FOR SIEVE PLATES

FIGURE 1



PREDICTED PENETRATION FOR 4 SIEVE PLATES
NO PARTICLE GROWTH

FIGURE 2

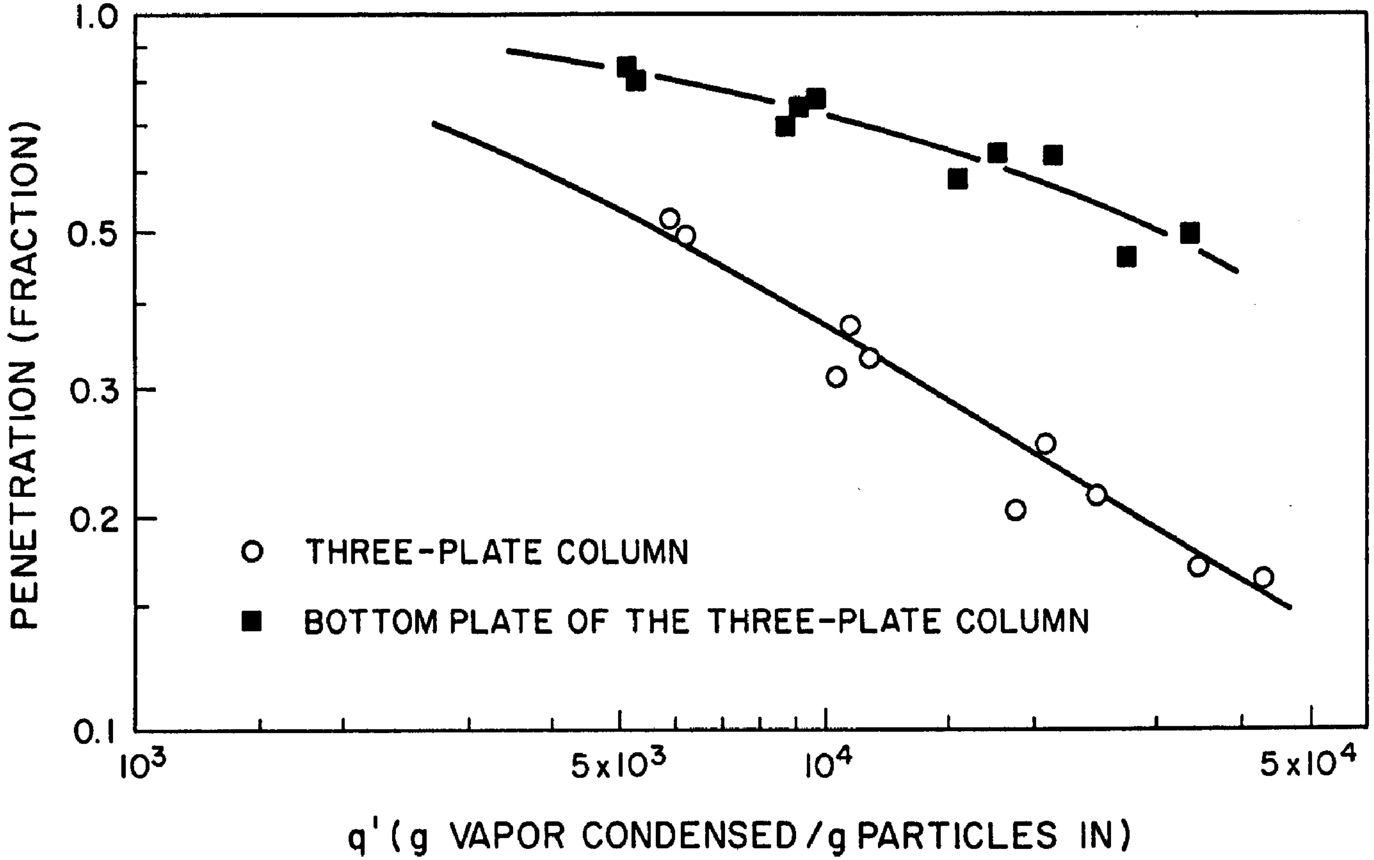


LEGEND:

1 VALVES
2 PRESSURE REGULATOR
3 ROTAMETERS
4 WATER COOLER
5 AIR PREFILTER
6 AIR BLOWER
7 AIR COOLER
8 VENTURI METER
9 AIR HEATER
10 "ABSOLUTE" FILTERS
11 PARTICLE CHARGE NEUTRALIZER
12 GAS MIXING SECTION
13 BOILER
14 STEAM ENTRAINMENT SEPARATOR
15 PRESSURE INDICATOR
16 AIR FILTER
17 PRESSURE INDICATOR
18 TWO-FLUID ATOMIZER
19 AEROSOL DRYER
20 IMPACTOR
21 SIEVE-PLATE SCRUBBER

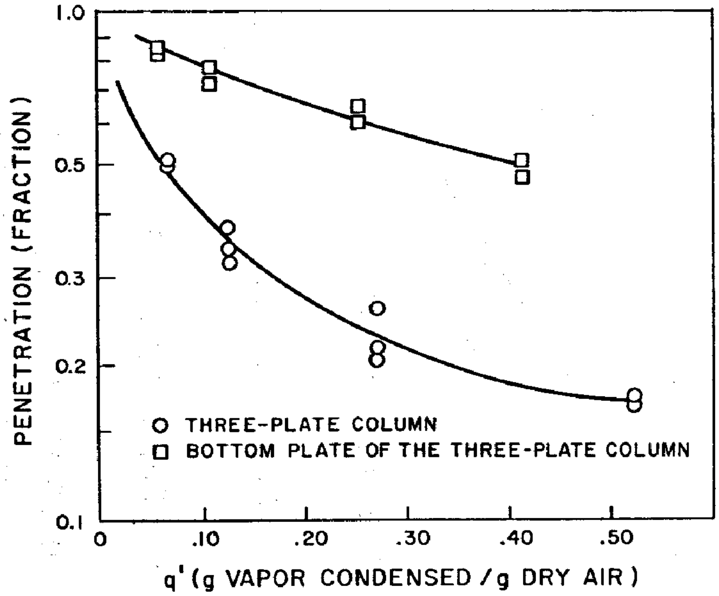
EXPERIMENTAL APPARATUS

FIGURE 3



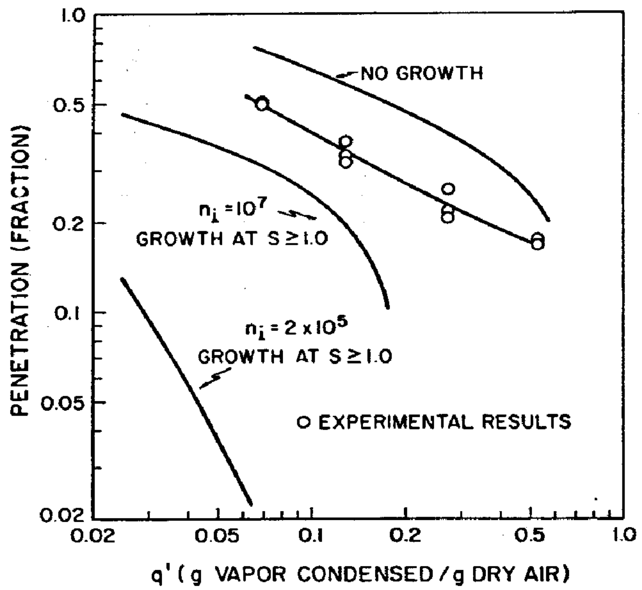
RELATIONSHIP BETWEEN PENETRATION AND VAPOR CONSUMPTION IN THE THREE-PLATE COLUMN

FIGURE 4



PERFORMANCE OF THE
THREE PLATE SCRUBBER

FIGURE 5



COMPARISON OF EXPERIMENTAL
RESULTS WITH PREDICTIONS
FOR A THREE PLATE SCRUBBER

FIGURE 6

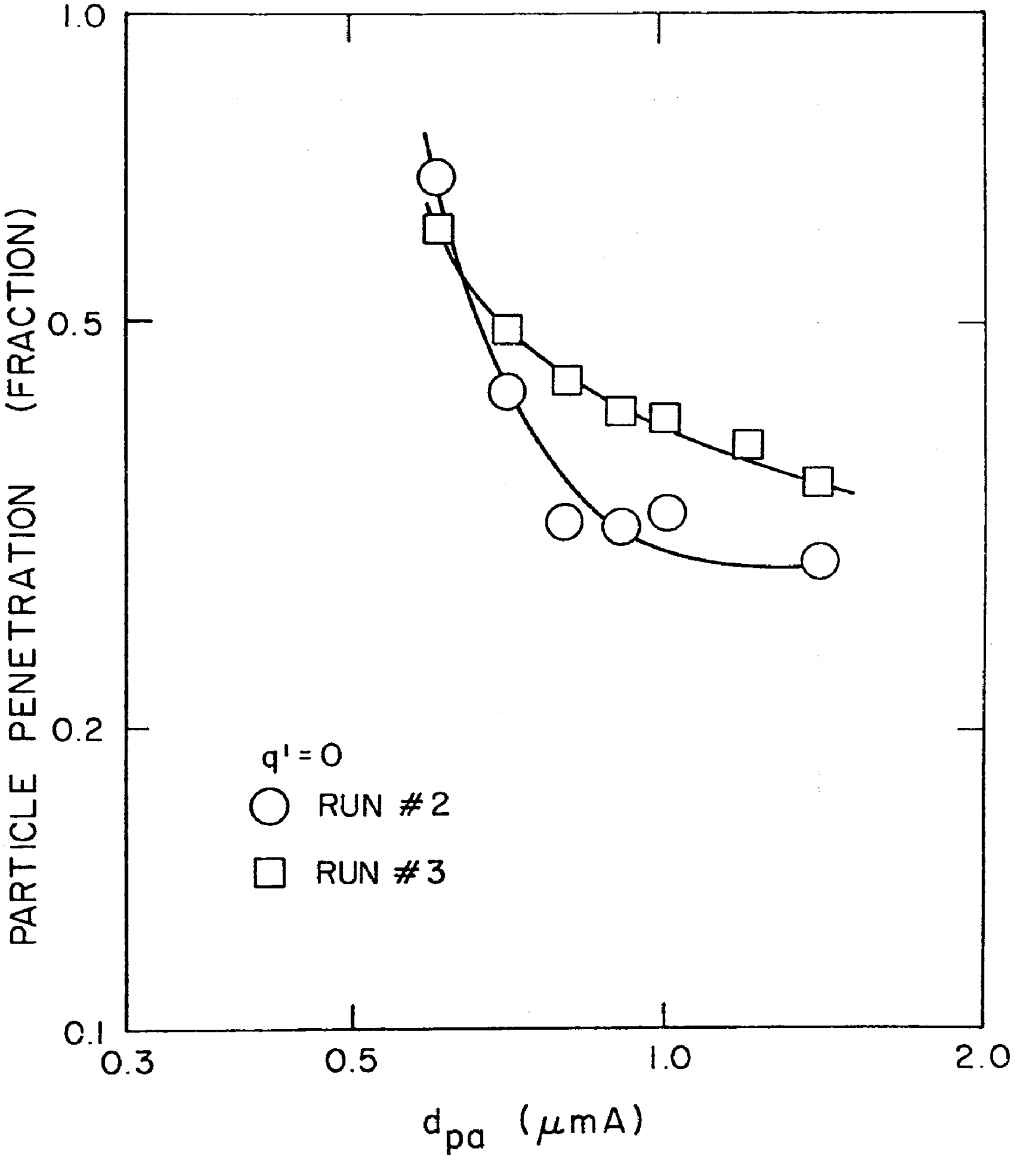


FIGURE 7 - PARTICLE PENETRATION VERSUS AERODYNAMIC DIAMETER.

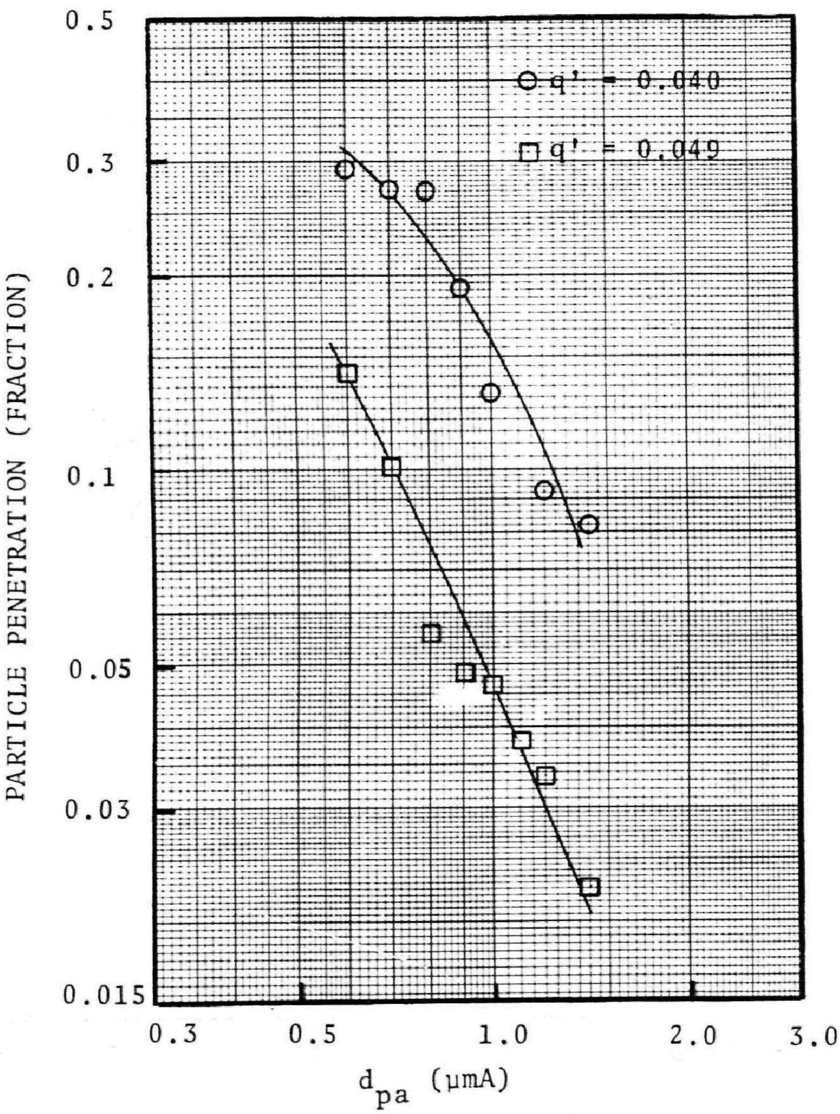


FIGURE 8 - PARTICLE PENETRATION VERSUS AERODYNAMIC DIAMETER

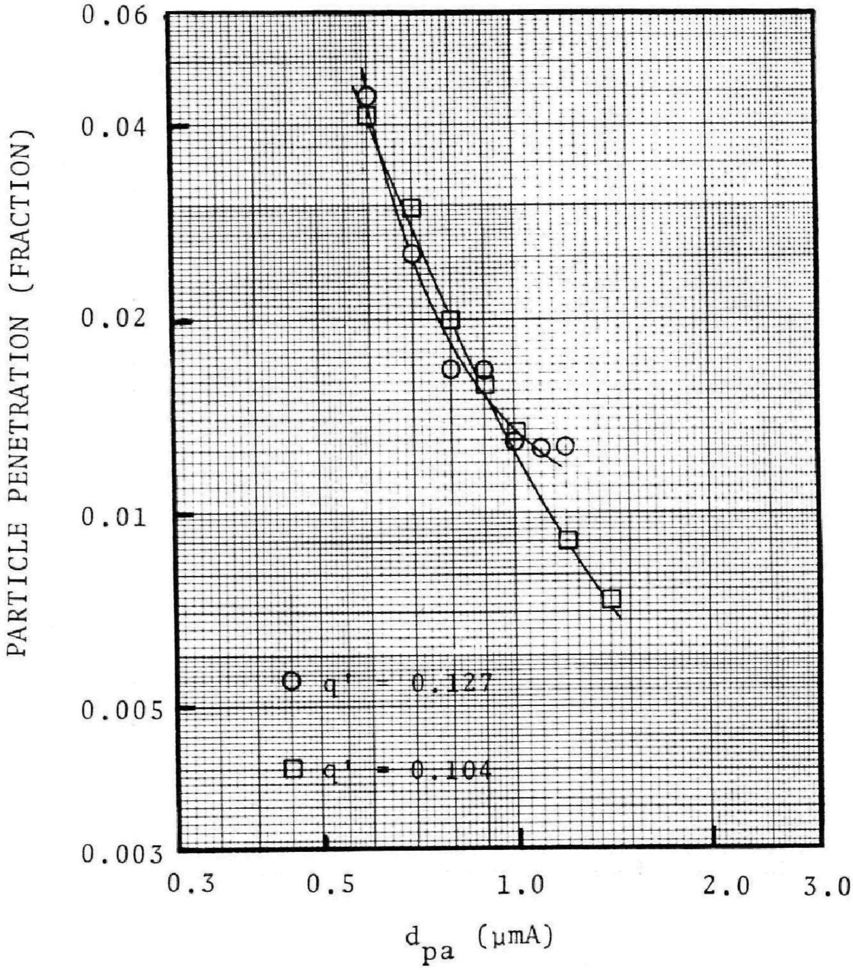


FIGURE 9 - PARTICLE PENETRATION VERSUS AERODYNAMIC DIAMETER

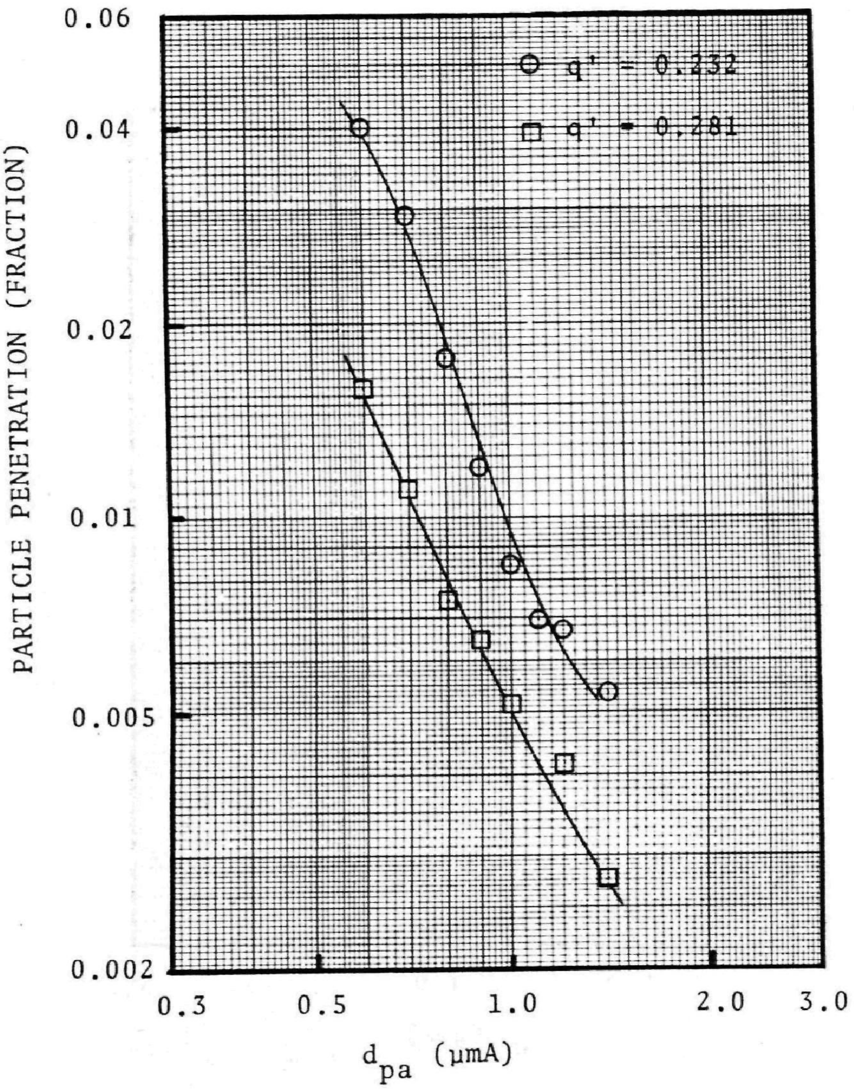


FIGURE 10 - PATICLE PENETRATION VERSUS AERODYNAMIC DIAMETER

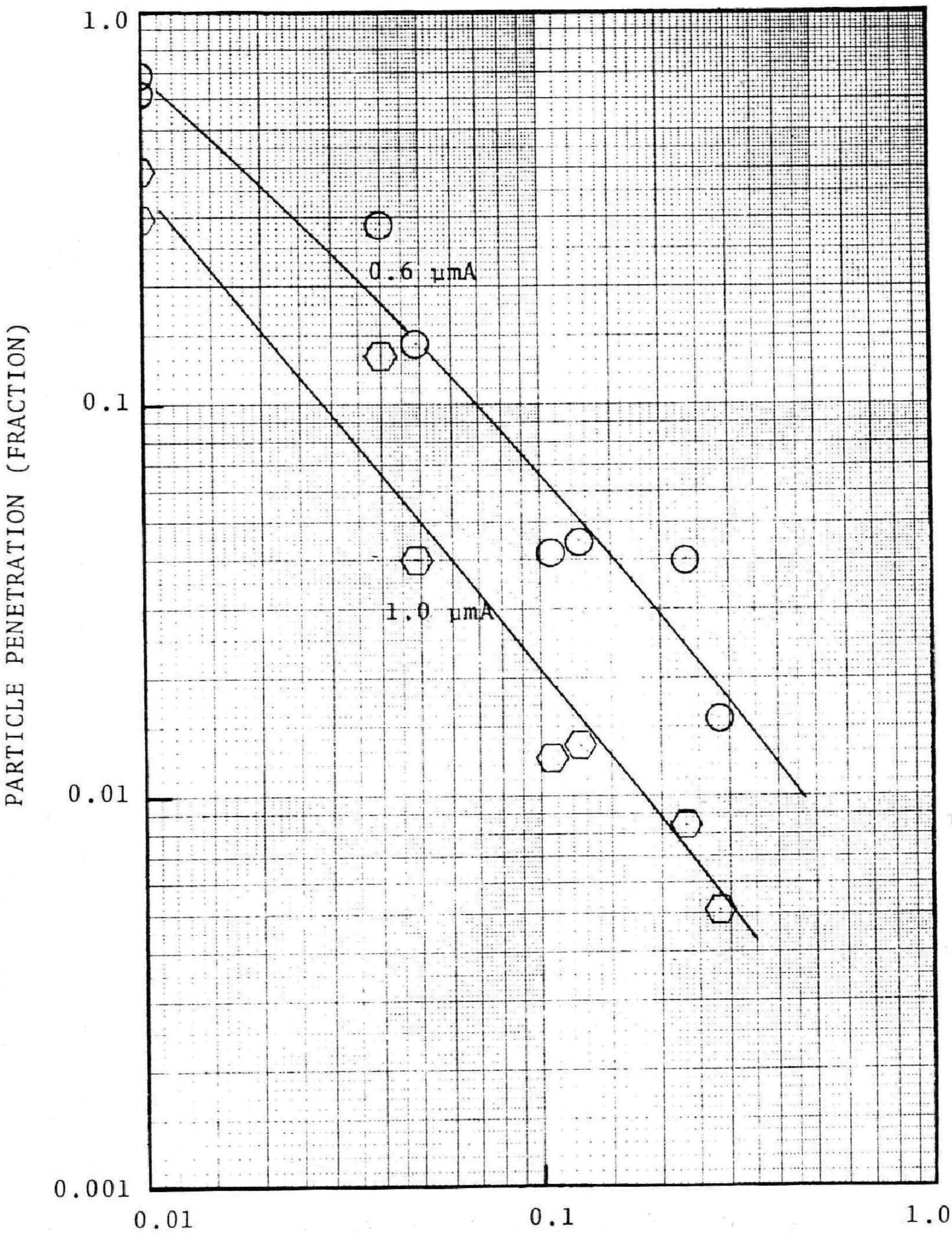

1.0
0.1
0.01
0.001
PARTICLE PENETRATION (FRACTION)
0.6 μmA
1.0 μmA
0.01
0.1
1.0
q' (g vapor condensed/g dry air)

FIGURE 11

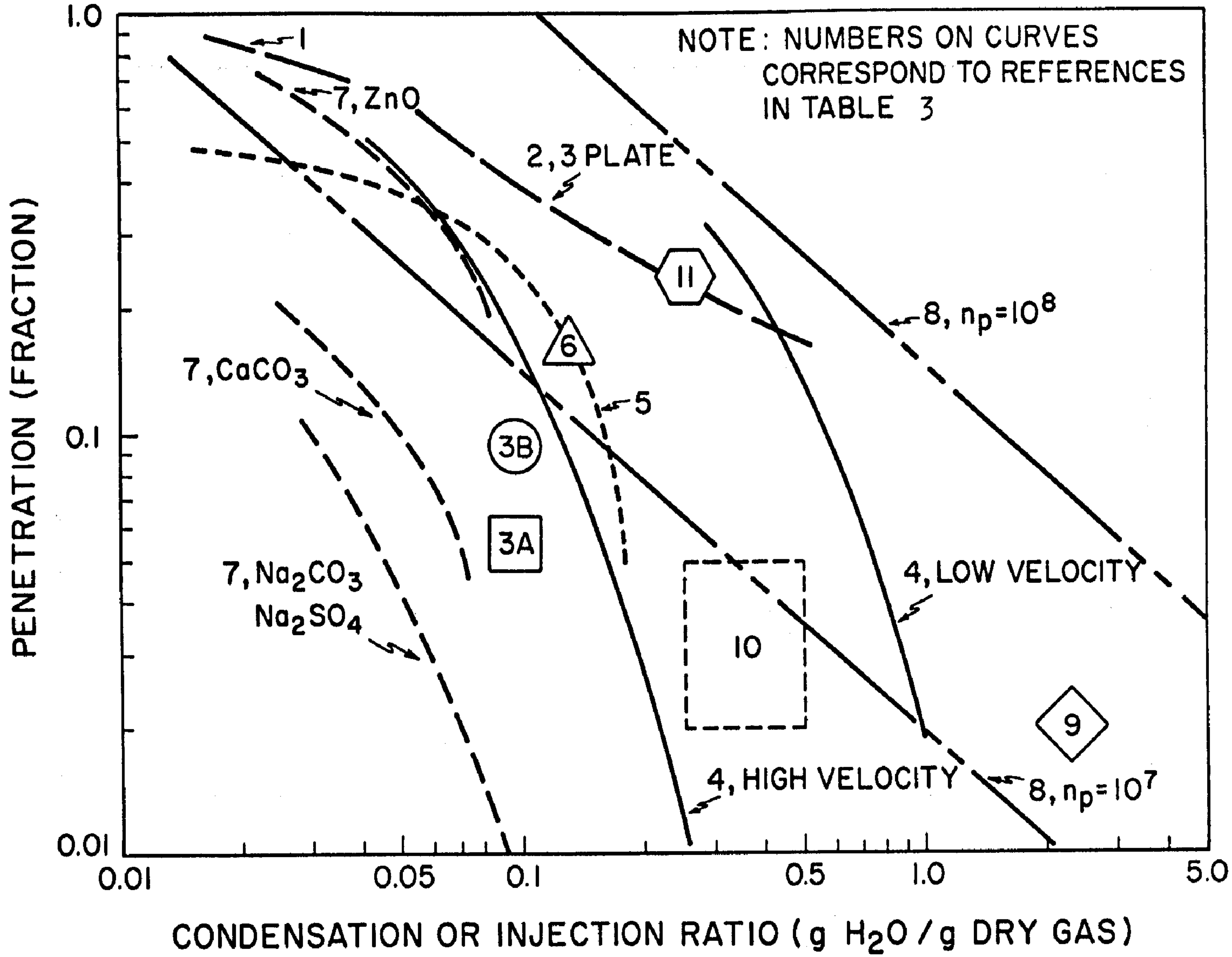
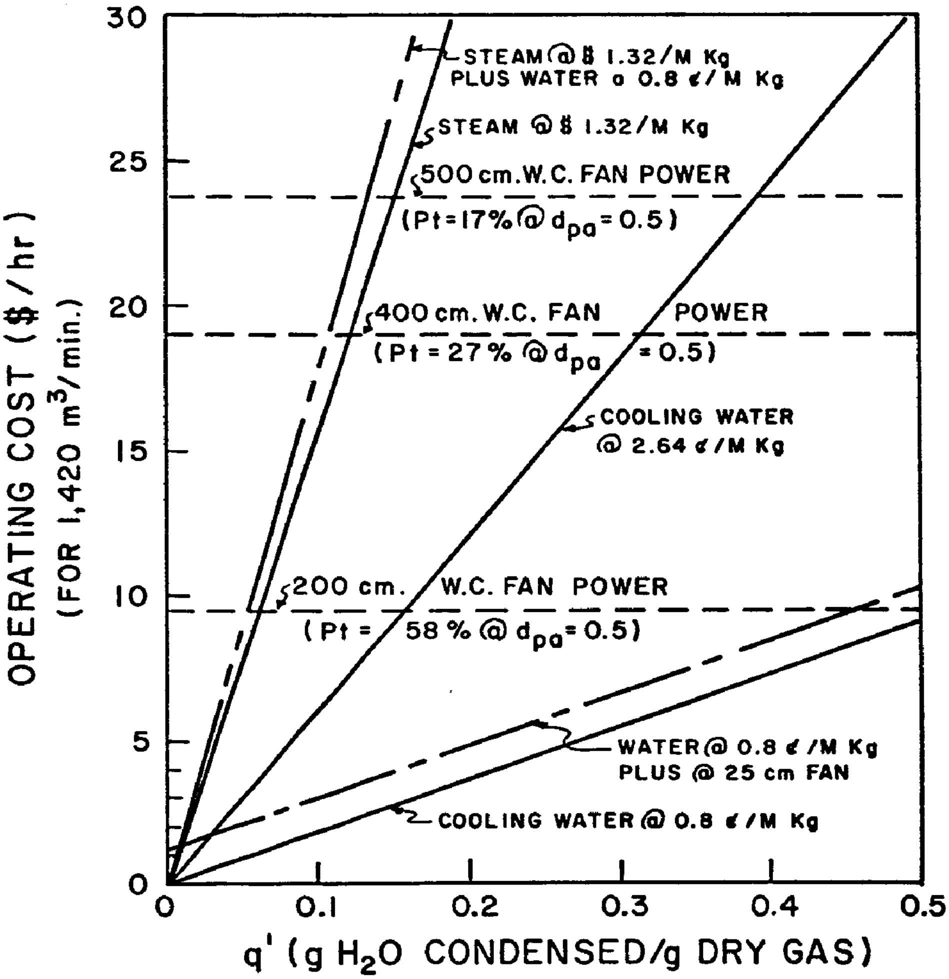

NOTE: NUMBERS ON CURVES CORRESPOND TO REFERENCES IN TABLE 3
1
7, ZnO
2, 3 PLATE
11
8, $n_p=10^8$
6
5
7, $CaCO_3$
3B
3A
7, Na_2CO_3
Na_2SO_4
10
4, LOW VELOCITY
9
4, HIGH VELOCITY
8, $n_p=10^7$
PENETRATION (FRACTION)
1.0
0.1
0.01
0.01
0.05
0.1
0.5
1.0
5.0
CONDENSATION OR INJECTION RATIO (g H_2O / g DRY GAS)

FIGURE 12



NOTES:

1. COSTS ARE FOR A 1,420 m^3/min. (50,000 CFM) SCRUBBER
2. PARTICLE DIAMETER, d_{pa}, IS AERODYNAMIC ($\mu m (g/cm^3)^{1/2}$)
3. POWER COST IS 1 ¢/KWH
4. FAN PLUS MOTOR EFFICIENCY IS 50%

OPERATING COSTS COMPARISON

FIGURE 13

FLUX FORCE CONDENSATION ASPIRATIVE WET SCRUBBING OF SUB-MICRON PARTICLES

by

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RP Industries, Inc.
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ABSTRACT

A novel aspirative wet scrubber system makes use of condensation forces to enhance fine particulate collection. A pressure gain of 2 to 4 inches, w.c. is generated by the system and total water pump power requirements for multi-stage systems are 2 horsepower per thousand s.c.f.m. of gas throughput. No fans or blowers are utilized. When scrubbing hot combustion products carrying 0.1 to 6.0 micron metal oxide particles from a kiln, total collection efficiency was 99.4%. Collection of fly ash, in the particle size range 0.1 to 10 microns, has been measured at 99.5% efficiency.

"Flux Force Condensation Aspirative Wet Scrubbing of Sub-Micron Particles"

by

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Condensation force enhancement of sub-micron particle collection in wet scrubbers has been the subject of a number of theoretical and small scale experimental studies in recent years. Sparks and Pilat (1970) have studied the improvement of sub-micron particle collection in wet scrubbers due to thermo and diffusiophoresis. S. Calvert et al. (1973) continued the studies of fine particle collection as enhanced by condensation forces. In addition, the Calvert et al. report includes a small-scale actual verification of the basic theory.

While condensation force scrubbing does indeed improve fine particle collection, the costs involved, as discussed by Calvert, are substantial. It was the objective of development activities at RP Industries, Inc. to reduce greatly the cost of condensation force scrubbing. It was a further objective to reduce significantly both the capital and operating costs of the equipment required for fine particulate removal. An additional objective was the development of large-scale wet scrubbing equipment that makes use of aspirative principles in order to reduce power consumption, and avoid the employment of fans or blowers, thus reducing maintenance requirements and enhancing system simplicity. The Dynactor is the trade name given to a patented aspirative gas/liquid/solids contactor/scrubber developed at RP Industries and it is the aspirative system discussed in this paper.

The scrubbing liquid, usually water, is introduced into a specially designed nozzle system at a pressure of up to 250 p.s.i.g. (according to application). The resulting high velocity shower of thin films and fine particles entrains air or gas as the shower diffuses into a reaction column. The result is establishment of a partial vacuum which is coupled to the source of air or gas by means of a radial impedance transformation section which acts to transform high pressure, low velocity gas into low pressure, high velocity gas with minimum losses. The principle involved can be described as the macroscopic application of diffusion pump techniques.

Conventional aspirators, using venturi eductor principles, require between 75 and 100 g.p.m. of motive liquid to aspirate each 1,000 c.f.m. of gas. Power requirements are thus reduced by more than an order of magnitude compared with earlier aspirative venturi eductors. Water usage is reduced by a factor of 15 to 20. Scrubbing systems up to 50,000 c.f.m. in throughput capacity are manufactured and marketed at the present time and it is expected that aspirative system capacities up to 1,000,000 c.f.m. will be available by the end of 1974.

DESCRIPTION OF EQUIPMENT

Figure 1 is a schematic diagram of a two stage system. Both stages are usually identical to one another. Scrubbing liquid is pumped from each reservoir/separator, as shown, to a specially designed nozzle system in each stage, at a pressure of 200 pounds per square inch. While this pressure may be varied, depending upon application, from 150 to 250 p.s.i.g., a typical delivery pressure is 200 p.s.i.g. Under these conditions the liquid is atomized into thin films and droplets of average thickness or diameter less than 500 microns.

This liquid discharge causing air or gas to be aspirated then continues to travel down the reaction column, where deliberately induced turbulence causes intimate contact to be maintained between gas and liquid. This results in physical and chemical equilibria to be produced by the time the mixed fluid exits from the reaction column into the separation reservoir.

By utilizing diffusion rather than Bernoulli principles, up to 4,800 standard volumes of gas is aspirated per volume of motive liquid. In gas scrubbing, 2,000 volumes of gas are aspirated per volume of liquid. In comparison, venturi eductors typically aspirate not more than 100 volumes of gas per volume of motive liquid. Two-stage aspirative systems typically consume a total of 2 horsepower per 1,000 a.c.f.m. (one hp. per stage per 1,000 a.c.f.m.).

The radial impedance transformation section is employed to couple efficiently the sources of air or gas at outside ambient pressure to the partial vacuum that obtains within the reaction column. Ambient gas at low velocity and higher pressure accelerates smoothly and continuously within the radial impedance transformation section. Thus, the potential energy of the influent gas is converted to kinetic energy at high efficiency.

The mixed fluid is separated into its liquid and gaseous components in the reservoir/separator sections of the system, as shown in Figure 1. A system of fixed baffles is utilized to ensure liquid/gas separation, which minimizes liquid carry-over. If influent gas carries small particles along with it, such particles are wetted and captured by the liquid throughout the entire length of the reaction chamber. By contrast, venturi wet scrubbers make effective contact between gas and liquid only in the constricted throat region. Contact time, therefore, is about 20 times longer than in venturi devices.

Table 1 shows the power requirements of a variety of scrubbing systems, including one, two, three, and four stages of each type of system. It is clear that the operation of a four stage aspirative system is less costly than operation of a single stage of many conventional wet scrubbing systems. Scrubbing efficiency increases geometrically with the number of scrubbing stages that operate in series with one another. For fine particle scrubbing, second, third, and fourth stages, regardless of system species, are often required to achieve high percentages of fine particle removal.

For example, if the influent gas is at a temperature above ambient, the first stage acts both to collect larger particles and to evaporate water. In the first stage, smaller particles are driven away from the water droplets by negative thermo-and diffusiophoresis, resulting in a decrease in the efficiency of fine particle collection. Moisture from the saturated warm air effluent from the first stage condenses on the scrubbing liquid in the second stage. The resulting positive thermo-and diffusiophoresis acts to increase significantly the efficiency of collection of fine particles. Thus, a two stage system permits the employment of condensation forces to enhance the scrubbing of fine particles - without the addition of any additional power.

The addition of a water spray to pre-condition the influent gas permits positive thermo-and diffusiophoresis to be utilized in multiple stages. The power required to spray small quantities of water into the influent gas stream is less than 1/10 horsepower per 1,000 a.c.f.m. of influent hot gas. Usually the temperature of the preconditioned, saturated gas remains above the temperature of the scrubbing water in both stages. The saturated air comes into contact with the cold water in each stage, which results in condensation of water vapor and this materially increases the efficiency of capture of sub-micron particles.

If a cold influent gas is to be scrubbed, steam can be added both to raise the temperature of the gas and to ensure water saturation. Under these conditions, additional energy is required to generate the steam, resulting in an increase in the cost of scrubbing fine particles. Generally speaking, the increase in power requirements is approximately equal to the power consumption of the aspirative system itself. For example, the 50,000 s.c.f.m. system power requirements are 100 horsepower and an additional 100 horsepower is required to generate the steam necessary.

DESCRIPTION OF TESTS

TEST #1

A two stage aspirative system was connected to the effluent from a cyclone whose input was hot gases issuing from a kiln. The kiln was fired by natural gas. The function of the process was the drying of a thickened metal oxide suspension in water in order to produce dry metal oxide powder. The system arrangement is shown in Figure 2. The kiln feeds a cyclone, in which most of the metal oxide powder above 6 microns is recovered. The gaseous output from the cyclone, containing metal oxide powder particles below 6 microns, is aspirated into the system. Figure 3 is a particle distribution curve of the metal oxide in the output of the cyclone.

A preconditioning water spray is introduced and the temperature of the gas which was 400°F at the output of the cyclone dropped to 150°F after preconditioning. Thus, condensation-force scrubbing was obtained in both stages.

Both input and output grain loading were measured isokinetically at 8 traverse points by a heated filter (600°F). The influent grain loading was measured at 1.95 grains per cubic foot. At the same time, the output showed a grain loading of 0.012 grains per cubic foot. The measurement time was 48 minutes - 6 minutes at each station. The total collection efficiency was 99.4%.

TEST #2

The efficiency of particle removal was measured in the collection of fly ash, in the particle size range 0.1 to 10 microns. In this case, the arrangement was constructed as shown in Figure 4. A simulated stack gas was created by a "salamander" powered by a #2 fuel oil. The temperature of the output of the salamander at 800 a.c.f.m. was 600°F. A powder feeder introduced fly ash into the hot gaseous effluent from the heat source at a grain loading of 0.74 grains per cubic foot. A preconditioning spray of water, four feet from the entrance of the system, reduced the gas temperature to 150°F. The fly ash grain loading at the output was measured at 0.004 grains per cubic foot. The measurements were made isokinetically as in the tests on metal oxide, described above. The overall particle capture efficiency was 99.5%.

TEST #3

Ambient air, dry bulb temperature 80°F, relative humidity 30%, was aspirated into the system at 1,000 a.c.f.m. Fly ash was added, using the same powder feeder as in Test #2, above. Again, the particle size range was 0.1 to 10 microns. There was no preconditioning either by water or steam. Input grain loading was measured at 0.82 grains per cubic foot. Output grain loading was measured at 0.02 grains per cubic foot. The efficiency of particle collection was 98.9%.

DISCUSSION

All single-stage wet scrubbers display a decrease in the collection of fine particles if the input gas is significantly hotter than the scrubbing liquid because of negative thermo-and diffusiophoresis. To overcome negative thermo-and diffusiophoresis, it is desirable to employ a preconditioning procedure to saturate the hot, dry, influent gas with water vapor.

As pointed out by Calvert, et al. (1973), added steam will successfully precondition hot, dry, influent gas. The cost for steam alone in one example is cited as 10.7¢ per 1,000 s.c.f.m. For a 50,000 s.c.f.m. scrubbing system the cost would be 35¢ per minute, $21. per hour - approximately $168,000. per year

(8000 hours). This cost is about equal to that of furnishing power to a 1,400 horsepower blower at 1.5¢ per kwh.

If the inlet gas is hot, steam need not be added and a preferred alternative is the use of two or more wet scrubber stages. In the first stage particles larger than several microns are collected efficiently and the second, third and fourth stages function as condensation-force scrubbers.

Generally, two aspirative stages suffice for most particulate scrubbing applications. At one horsepower per 1,000 a.c.f.m. per scrubbing section, a two-stage, 50,000 a.c.f.m. system will operate at a cost of $1.50 per hour, $12,000. per year.

The foregoing tests have established that the scrubbing efficiency of the tested system compares favorably with the particle scrubbing efficiency of conventional high energy venturi scrubbers but at much lower operating cost. Further, maintenance and other problems surrounding the use of powerful blowers and fans are not present in aspirative systems. The only moving parts are the pumps which furnish the scrubbing liquor to the system at 200 p.s.i.g. and at flow rates of 5 g.p.m. per 1,000 c.f.m. Makeup liquid is usually introduced into the system at 10% of the recirculation of the scrubbing liquid. For the scrubbing of 50,000 a.c.f.m., 25 to 50 g.p.m. of water usually is required both to replenish evaporated scrubbing liquor as well as to flush captured contaminants out of the system.

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50,000 A.C.F.M. SCRUBBER	PRESSURE DROP " W.C.	HORSEPOWER FAN	HORSEPOWER PUMP	$ COST/YEAR POWER (8000 HRS/YR.) (1.5¢/K.W.Hr.)
SINGLE STAGE				
ASPIRATIVE	1" GAIN	0	50	6,000
VENTURI	44	535	21	66,700
TRAY	15	183	2.5	22,250
EDUCTOR (VENTURI)	1" GAIN	0	225	27,000
TWO STAGES				
ASPIRATIVE	2" GAIN	0	100	12,000
VENTURI	88	1070	42	133,400
TRAY	30	366	5	44,500
EDUCTOR (VENTURI)	2" GAIN	0	450	54,000
THREE STAGES				
ASPIRATIVE	3" GAIN	0	150	18,000
VENTURI	132"	1605	63	200,000
TRAY	45"	549	7.5	66,750
EDUCTOR (VENTURI)	3" GAIN	0	675	81,000
FOUR STAGES				
ASPIRATIVE	4" GAIN	0	200	24,000
VENTURI	176"	2140	84	266,800
TRAY	60"	732	10	89,000
EDUCTOR (VENTURI)	4" GAIN	0	900	108,000

TABLE 1

POWER REQUIREMENTS AND COSTS

DYNACTOR SCHEMATIC

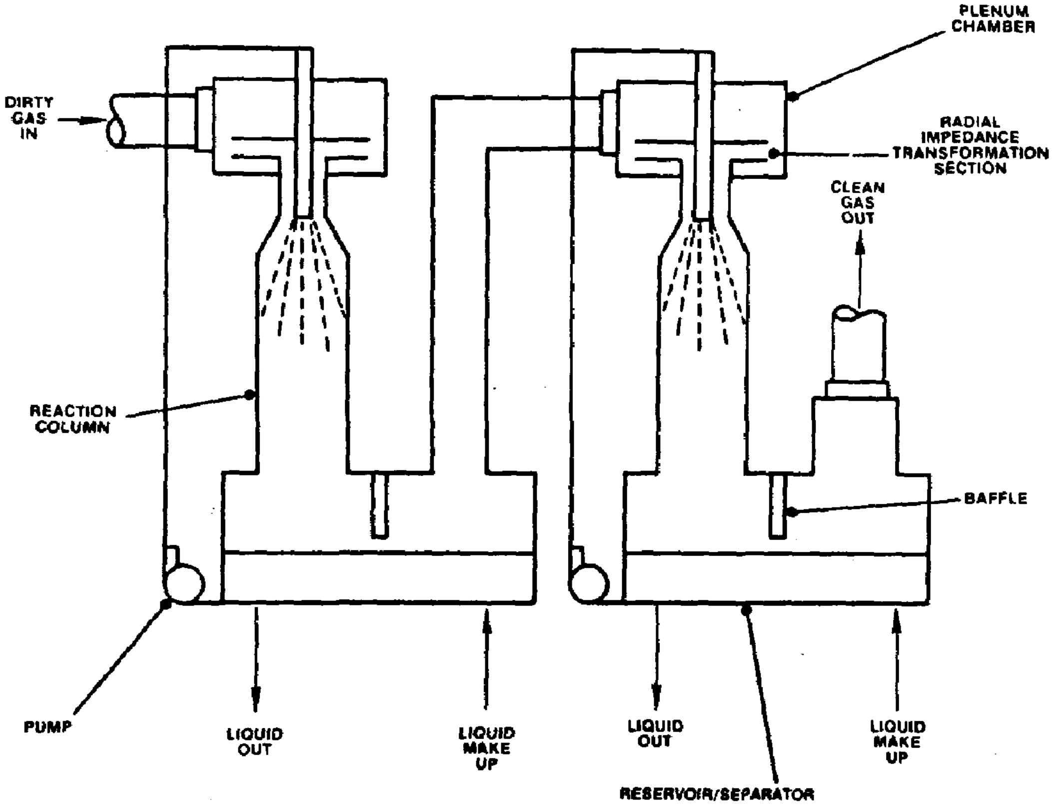


FIGURE I

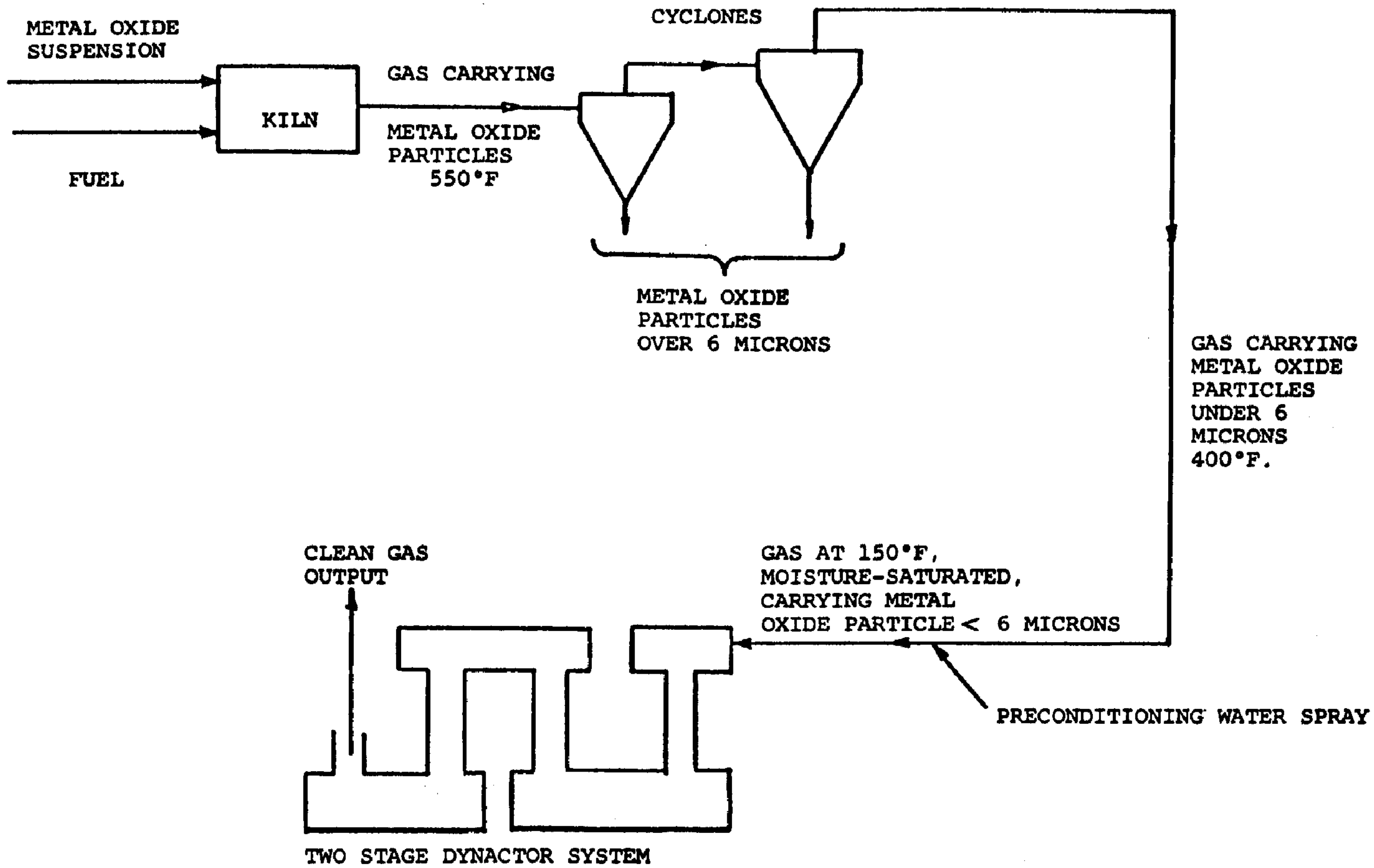
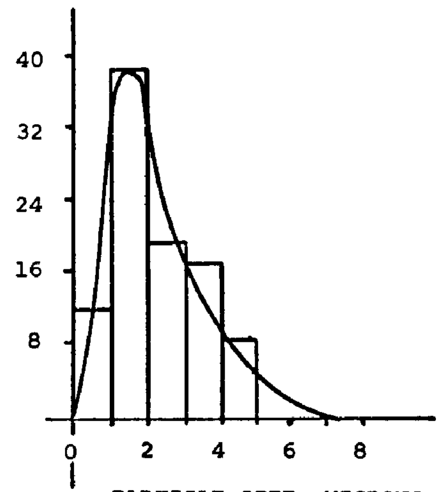


FIGURE 2 - CONDENSATION-FORCE WET SCRUBBING OF FINE METAL OXIDE PARTICLES

FIGURE 3

PARTICLE DISTRIBUTION OF METAL OXIDE IN OUTPUT OF CYCLONES



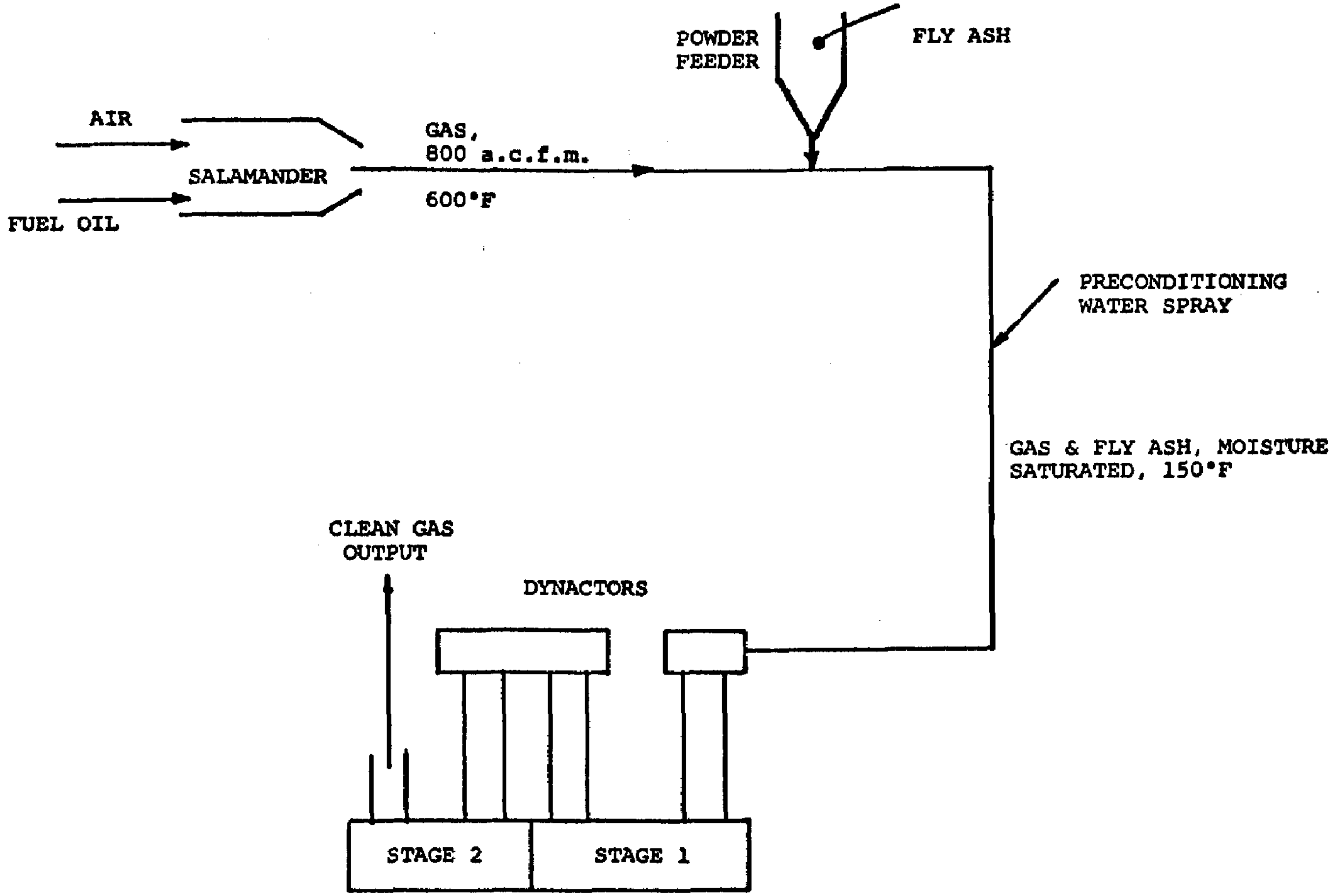


FIGURE 4 - CONDENSATION FORCE DYNACTOR SCRUBBING OF FLY ASH

ENTRAINMENT SEPARATORS FOR SCRUBBERS

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ABSTRACT

Liquid entrainment separation was studied experimentally for packed bed, knitted mesh, zigzag baffle, tube bank, and cyclone type apparatus. Primary collection efficiency data compare well with theoretical predictions but re-entrainment of the collected liquid did not agree with theoretical models. Separation efficiency, drop size, and pressure drop data are presented.

"Entrainment Separators for Scrubbers"

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Gas emerging from wet scrubbers and other types of equipment such as evaporators, boilers, and stills carries with it small drops of liquid. In the past little attention was paid to entrainment separator design but the increased use of scrubbers in power plants and other sources have shown that problems with entrainment separators can be very significant. The entrainment separator is no longer viewed as a minor part of the scrubber body but represents a significant investment and operating cost.

Drops formed from bursting bubbles have a bimodel distribution with mass median diameter for small drops around 40 μm and for large drops above 1,000 μm. The drops formed by tearing of liquid sheets and ligaments and by splashing of liquid drops are 200 μm and larger. The mist formed by the condensation of saturated vapor contains sub-micron drops.

The entrained drops generated by scrubbers are quite large, so that separators utilizing gravitational and inertial forces are suitable. Devices such as packed beds, fibrous beds, cyclones, louvers or zigzag baffles or chevrons, and banks of rods are used for entrainment separation. Once the drops are captured (this is what we call "primary collection"), the resulting coalesced fluid must be removed from the separator without being re-entrained by the gas. Thus the overall performance includes the effects of both primary collection and reentrainment.

A literature search revealed that equations to predict primary collection efficiency and pressure drops are available for most of the entrainment separators except for the zigzag baffle type. Some of the problems the present day entrainment separators face are absence of reliable data and design equations, plugging, reentrainment and drainage. The purpose of the present study is to define performance as a function of gas and liquid flow rates and other parameters.

Theoretical Predictions

Theoretical equations for determining the primary collection for most entrainment separator types are summarized by Calvert et al. (1972). However, theoretical equations for zigzag baffles had not previously been developed. A model has been derived in this study for the prediction of primary collection efficiency in baffle type separators, based on inertial mechanisms:

$$E = 1 - \exp - \left(\frac{u_t}{u_G} \frac{n\ w\ \theta}{b \tan \theta} \right) \qquad (1)$$

where, E = fractional collection efficiency

b = distance between baffles normal to gas flow, cm

u_t = drop terminal velocity, cm/sec

u_G = superficial gas velocity, cm/sec

n = number of rows of baffles

w = width of the baffle, cm

θ = angle of baffle from flow direction, radian

It was also necessary to develop a mathematical model to predict pressure drop in a baffled separator. The following derivation is based on the drag coefficients for plates inclined to the flow.

Fage and Johansen (1927) present drag coefficients as a function of angle incidence, θ, for plates inclined to the flow.

$$\Delta P = \sum_{i=1}^{n} f_D \left(\frac{A_d}{A_T} \right) \rho_G \left(\frac{u_G^2}{2} \right) \qquad (2)$$

where, A_d = projected frontal area, cm^2

A_T = total flow cross sectional area, cm^2

f_D = drag coefficient for a plate inclined at angle "θ"

θ	30°	45°	60°	90°
F_D	0.65	0.85	0.78	1.07

For the baffles after the first row, the angle of incidence to the flow is doubled and the fraction of the flow cross section covered by the projected drag area also increases.

Mathematical models for reentrainment in horizontal and vertical baffle separators and in cyclones were also derived in this study. However, the predicted reentrainment velocities are much lower than the experimental.

EXPERIMENTAL PILOT PLANT

Experimental studies were made in a pilot plant with gas flow capacity of 85 m^3/min (3,000 cfm). The test sections are large enough to have minimal wall effects for packed separators and provide a fairly long collection element when cross-flow effects are important. The apparatus includes an air prefilter, blower, air heater, spray section, test section, observation section, feed and catch tanks, control panel and measuring devices.

Detailed descriptions of the separators which were studied are as follows:

1. Mesh - Model 4CA (ACS Industries). Type - layered, (with crimping in alternate directions). Density = 0.144 g/cm^3. Wire diameter = 0.028 cm. Percent voids = 98.2%. Mesh surface area = 2.8 cm^2/cm^3. Thickness = 10 cm. Material of construction = AISI 304.
2. Packed Bed - Packing - 2.5 cm Pall rings. Specific surface = 1.9 cm^2/cm^3. Density = 0.088 g/cm^3. Material of construction = Polypropylene plastic. Bed length = 30 cm.

3. Zigzag Baffle Section - Baffle dimension = 7.5 cm width x 61 cm high x 0.16 cm thick. No. of rows = 6. Spacing between rows = 2.5 cm. Angle between baffle surface and air flow direction = 30^{o}. Spacing between baffles in a row = 7.3 cm. See Figure 1.
4. Bank of Tubes - Number of rows = 6. External diameter = 1.9 cm. Length = 61 cm. Number of tubes in a row = 8. The tubes were equispaced. See Figure 1.
5. Cyclone - The cyclone is a cylinder 61 cm diameter x 243 cm overall height. The cyclone inlet is 30.5 cm high and 15 cm wide, giving a maximum inlet velocity of 3,000 cm/sec. Higher velocities were studied by using a vane in the inlet. The design is described by Stearman and Williamson (1972) and is a straight cylinder with flat bottom.

Entrainment separators numbers 1, 2, 3 and 5 were selected because they are the most common separators in industrial use. Banks of streamlined struts are reported to operate at low pressure drop, with high efficiency and a high reentrainment velocity. Although this type of separator is not in common use, it appeared promising enough to study.

The range of major variables studied is given below:

Drop diameter = 82 to 1,600 μm.

Air velocity = 100 to 750 cm/sec in all except 400 to 500 cm/sec for the cyclones.

Liquid flow rate = 10^3 to $4x10^4$ cm^3/min

Air flow rate = 8-85 m^3/min

Sampling Procedure

Drop size determination. The drop size in the experiments varied between 40-2,000 μm. Filter papers coated with 1% potassium ferricynide and ferrous ammonium sulphate were used to determine the drop diameters. The grain size of the chemicals normally limit the lower diameter by this method to 5 to 10 m. A correlation given by Chilton (1952) is used to convert blot diameter on filter paper to actual drop diameter.

In a few runs, isokinetic sampling through a filter holder containing treated filter was done to measure entrainment drop diameter. This method is used when the collection efficiency of a filter paper held in air would be too low for small drops.

The determination of entrainment loading involved taking an isokinetic sample through a nozzle which was heated to evaporate the entrainment. Humidity was measured by dry and wet bulb thermometers at the end of the nozzle. Fifteen (15) samples at 4 cm interval were measured along the vertical height of the duct to get average value of entrainment. When the liquid loading was large an impactor with about an 8.0 μm cut diameter was used before the nozzle and the liquid caught in the impactor was added to that determined by the evaporation technique.

EXPERIMENTAL RESULTS

Collection efficiency versus gas velocity for the baffle type entrainment separator is presented in Figure 2. A theoretical curve for the collection efficiency of mist with d_{pg} = 90 μm and geometric standard deviation of 1.35 is shown by a solid line in Figure 2.

Experimental data for the collection of mist with d_{pg} = 380 μm in zigzag baffles is compared with other data from the literature in Figure 3. Results reported by Bell and Strauss (1973) for zigzag baffles are plotted in Figure 3 and it can be seen that the collection efficiencies of the present study were much higher. This is due to Bell's smaller number of rows (4), non-staggered baffles, smaller width of baffles (6.2 cm) and large distance between baffles (8.8 cm).

The solid line in Figure 3 represents Houghton and Radford's (1939) data for equipment comparable to ours. Their experiments were conducted with two droplet distributions in the inlet. These results are comparable with the present results due to similarities in the design.

Packed bed efficiency data are presented as points for several drop sizes in Figure 4 and it can be seen that at velocities lower than 600 cm/sec there was no penetration. The solid line was predicted for primary collection by means of the method given in the "Scrubber Handbook". The data agree well with the theory.

The overall efficiency data for a tube bank and for knitted mesh are also shown in Figure 4. The efficiency in all the runs was nearly 100%. Penetration of drops (with mass median diameter 84 μm) was observed at velocities below 240 cm/sec in the tube bank.

Experimental collection efficiency in the cyclone with and without an inlet vane is shown in Figure 5. The collection efficiency was 100% throughout the experimental range. The gas velocity without inlet vane was varied from 800 cm/sec to 2,300 cm/sec and with inlet vane was varied from 1,600 cm/sec to 3,700 cm/sec.

Pressure Drop

Experimental dry pressure drop (air flow only) for baffles agree well with the theory. The dry pressure drop versus gas velocity relationships for packing, baffles, tube bank, and mesh are shown in Figure 6. It should be noted that the efficiencies of different separators at a given velocity are not the same.

The effect of liquid load on pressure drop was found to be negligible except in the knitted mesh. For $0 < L/A < 1$, the pressure drop in the mesh was $1.5\ \Delta P_{dry}$ and for $0 < L/A < 5$, the pressure drop was $2.3\ \Delta P_{dry}$. Here, L/A is the superficial liquid velocity, cm/min. A similar effect of liquid load on pressure drop in mesh was also found by York (1954).

The pressure drop data of Houghton and Radford (1939) compare well with the present results. The higher pressure drop obtained by Houghton and Radford may be due to no spacing between the rows and lips on the fourth and fifth row of baffles. For the tube banks they give comparable results at velocities lower than 500 cm/sec. At higher velocities, the present study gives higher pressure drops, which may be due to smaller spacing between the rows and to cylindrical tubes rather than streamlined tubes. Houghton and Radford's pressure drop data for knitted mesh lie within our results for $L/A = 0$ and $1 < L/A < 5$.

The dry pressure drop is plotted against geometric average gas velocity in the cyclone inlet and outlet in Figure 7. As seen in the figure the data correlate well along a straight line. Shepherd and Lapple's (1940) pressure drop correlation for cyclones with inlet vane is plotted for comparison. Their prediction is 2.7 times higher than the present pressure drops.

Reentrainment

Table 1 gives the conditions observed for onset of reentrainment and shows that the velocity for onset of reentrainment decreases with increase in the liquid load. The mass median outlet drop diameter increases with gas velocity, as is shown in Figure 8.

The effect of liquid load, at a constant gas velocity, was to decrease the mass median drop diameter of the reentrainment. At 600 cm/sec gas velocity, increasing the liquid flow rate from 7.6 ℓ/min to 13.3 ℓ/min, the mass median drop diameter decreased from 265 μm to 185 μm. Bell and Strauss measured the drop size distribution of entrainment coming out of baffle type separator. Their results are comparable with the drop size distribution found in the present study.

The minimum outlet drop sizes found for the separators tested are shown in Figure 9. Outlet drop size distributions for 82 μm drops entering baffles at 600 cm/sec air velocity and a water flow rate of 3.3 ℓ/min (0.86 GPM) was d_{pg} = 430 μm and σ_g = 1.7, and at 5 ℓ/min (1.33 GPM), d_{pg} = 620 μm and σ_g = 1.7. For the smaller size distribution, 0.01% of the drops are smaller than 60 μm diameter.

Figure 10 shows the performance of baffle type separator. The shaded region shows the onset of reentrainment. The reentrainment observed in all the experiments was 0.5-1%. The theoretical model is based on ideal conditions and therefore predicts reentrainment at higher velocities.

In Figure 11, experimental data for the onset of reentrainment are plotted for various entrainment separators. The ordinate represents the actual liquid to gas volumetric ratio approaching the entrainment separator. The onset of reentrainment velocity decreases as the liquid to gas ratio is increased.

It should be pointed out that the design of the liquid drainage path is quite important. An overdesign will lead to flow of gas where liquid is to be collected and reentrainment will result. An underdesign will result in liquid creeping in the entrainment separator floor leading to reentrainment.

CONCLUSIONS

1. The theoretical models presented for calculating primary efficiency and pressure drop for baffle section show good agreement with experimental data.
2. The pressure drop in cyclone varies as a square of geometric average velocity in the cyclone inlet and outlet.

3. The effect of liquid load on pressure drop is negligible in the packed bed, baffles, tube bank and cyclone.
4. Collection efficiency in the experimental range is nearly 100% with 0.5% to 1% reentrainment at higher gas velocities.
5. The mass median drop size for reentrainment varies between 25-650 μm.
6. The minimum drop size present in the reentrainment is 40 μm.

Table 1. EFFECT OF LIQUID LOAD ON REENTRAINMENT IN DIFFERENT ENTRAINMENT SEPARATORS.

Test Section	Average Mass Median Diameter	Average Liquid Load cm^3/sec	Onset of Reentrainment
Tube Bank	90 μm	$4x10^2$	150
Tube Bank	350 μm	$2.7x10^2$	350
Mesh	170 μm	$4x10^2$	180
Mesh	260 μm	$1.5x10^2$	450
Zigzag Baffles	700 μm	$2.7x10^2$	150
Zigzag Baffles	700 μm	$4x10^2$ $2.7x10^2$	300

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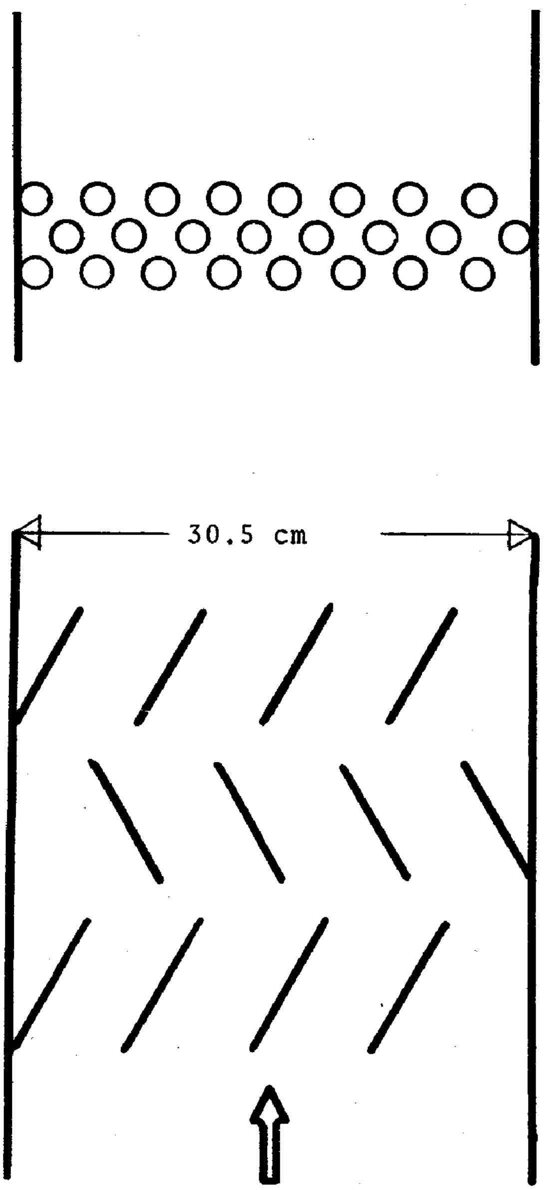
FIGURE 1
SEPARATOR SKETCHES



TUBE BANK
(3 ROWS SHOWN)

ZIGZAG BAFFLES
(3 ROWS SHOWN)

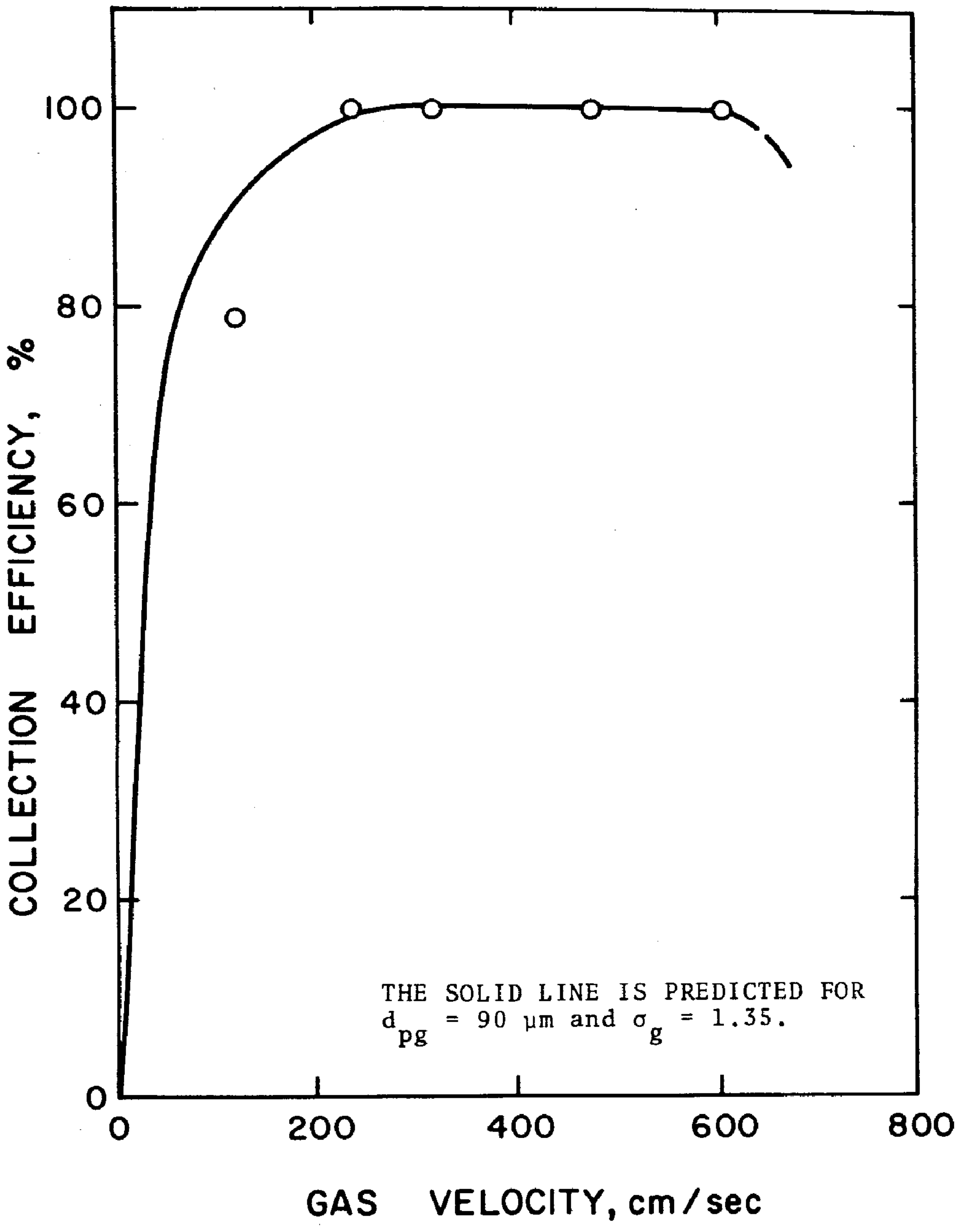


FIGURE 2

COLLECTION EFFICIENCY VERSUS GAS VELOCITY IN ZIGZAG BAFFLES WITH $n = 6$ and $\theta = 30°$.

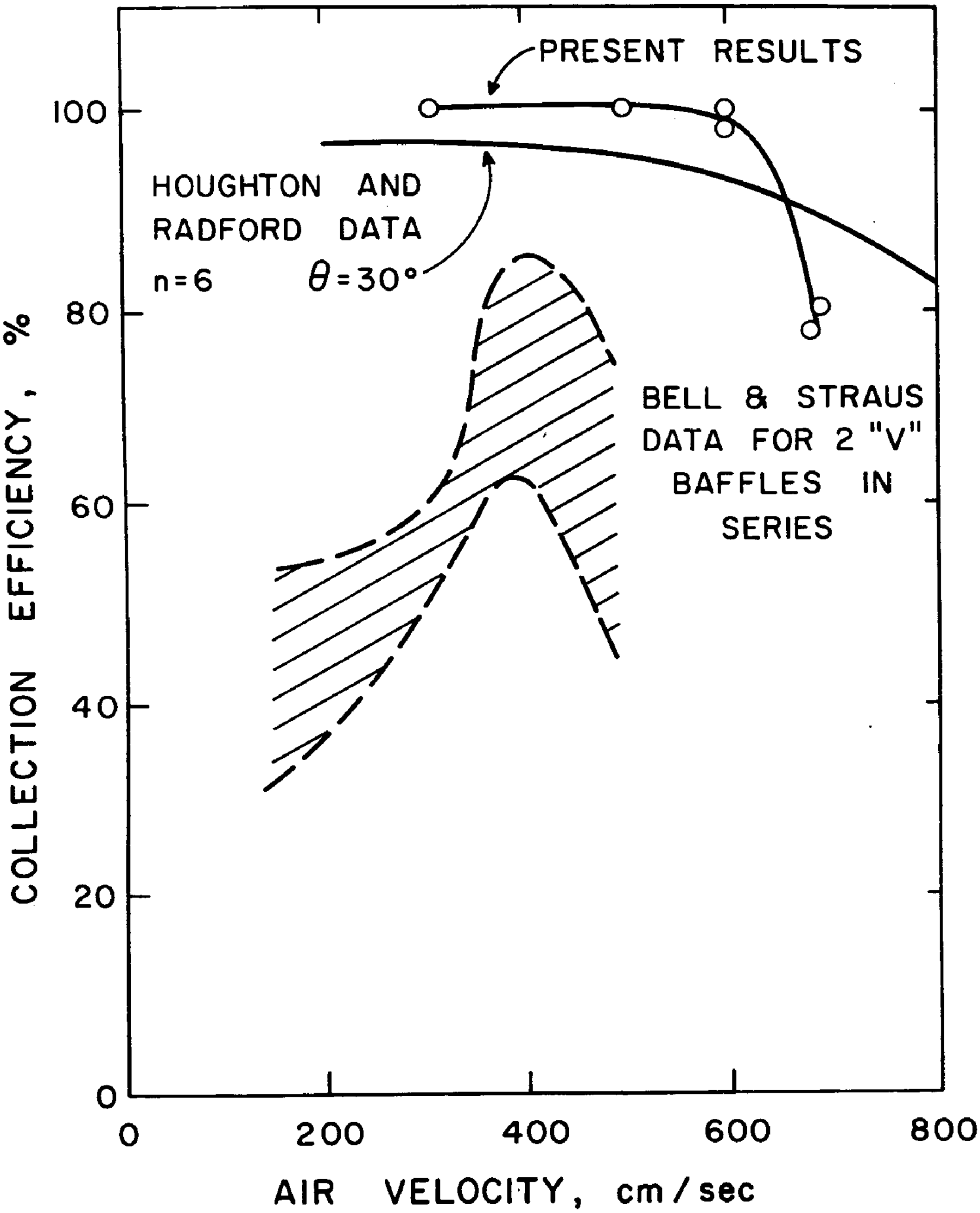
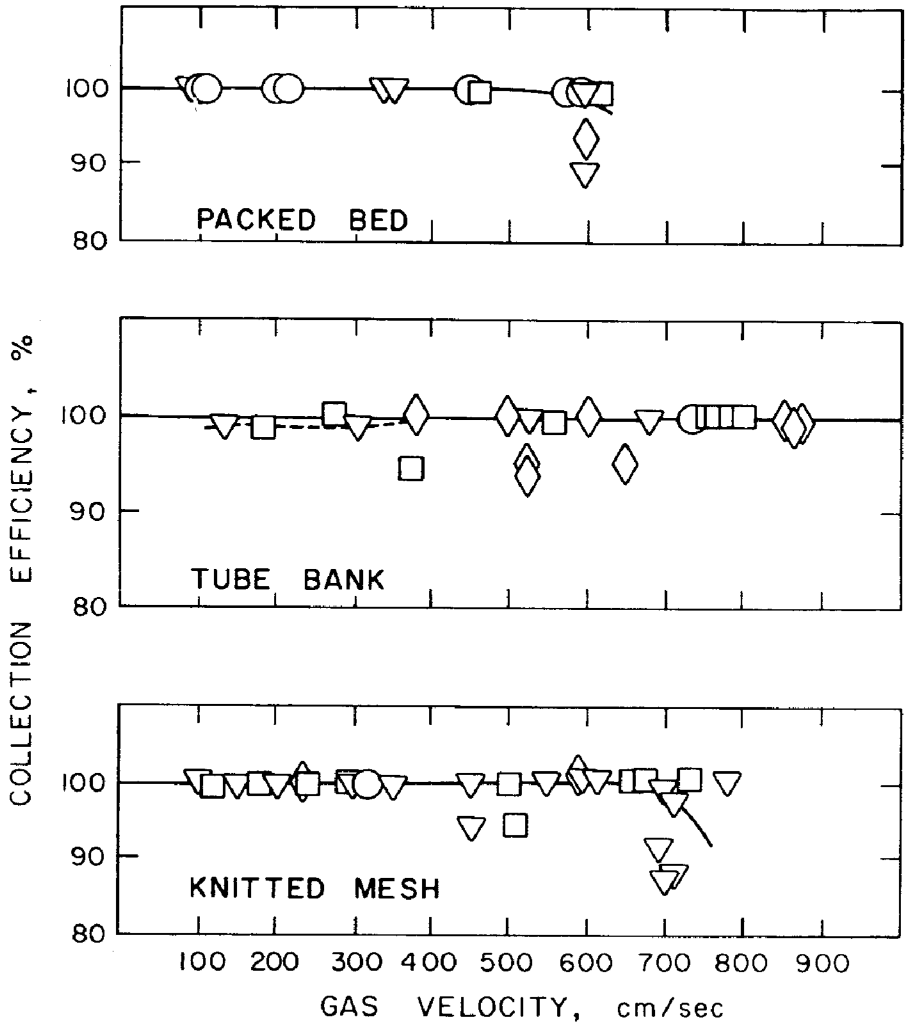


FIGURE 3

COMPARISON OF PRESENT STUDY WITH LITERATURE DATA FOR HORIZONTAL GAS FLOW IN ZIGZAG BAFFLES.



EXPERIMENTAL COLLECTION EFFICIENCY AS A FUNCTION OF GAS VELOCITY IN A PACKED BED, TUBE BANK AND KNITTED MESH WITH HORIZONTAL GAS FLOW.

INLET DROP DIAMETER, μm

▽ 84

◇ 380

□ 1,225

○ >1,225

FIGURE 4

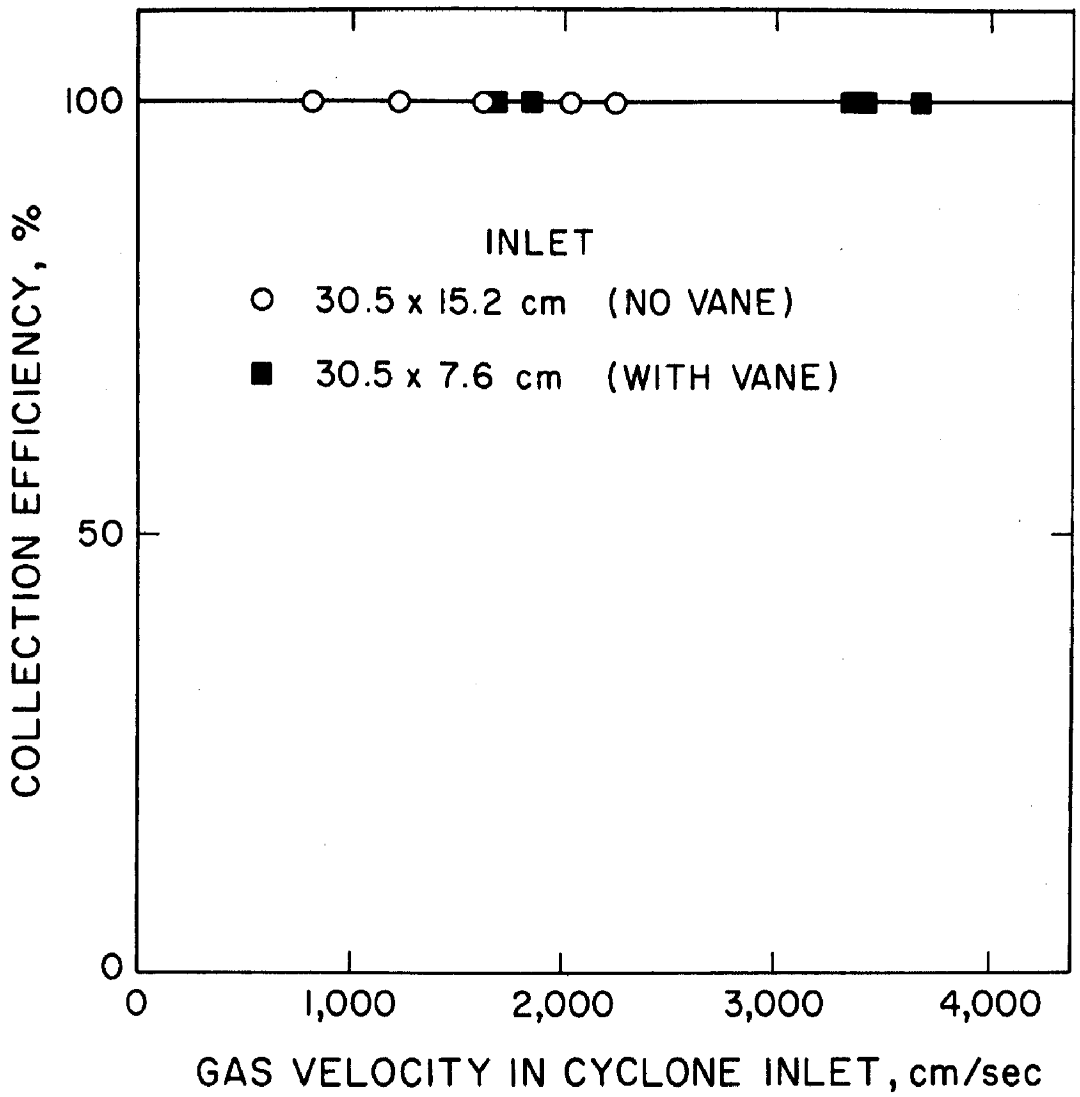


FIGURE 5

EXPERIMENTAL COLLECTION EFFICIENCY IN CYCLONE.

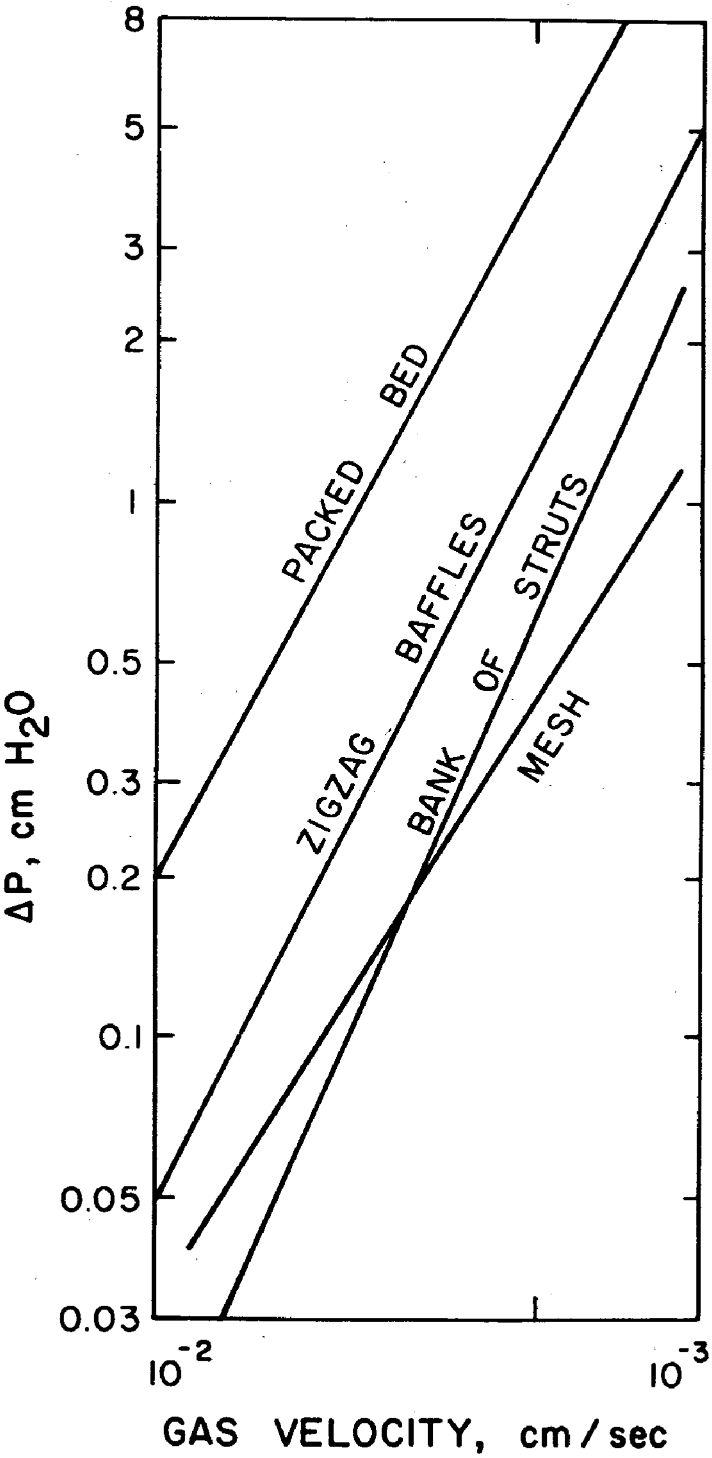


FIGURE 6

DRY PRESSURE DROP VERSUS GAS VELOCITY IN DIFFERENT SEPARATORS USED IN PILOT PLANT.

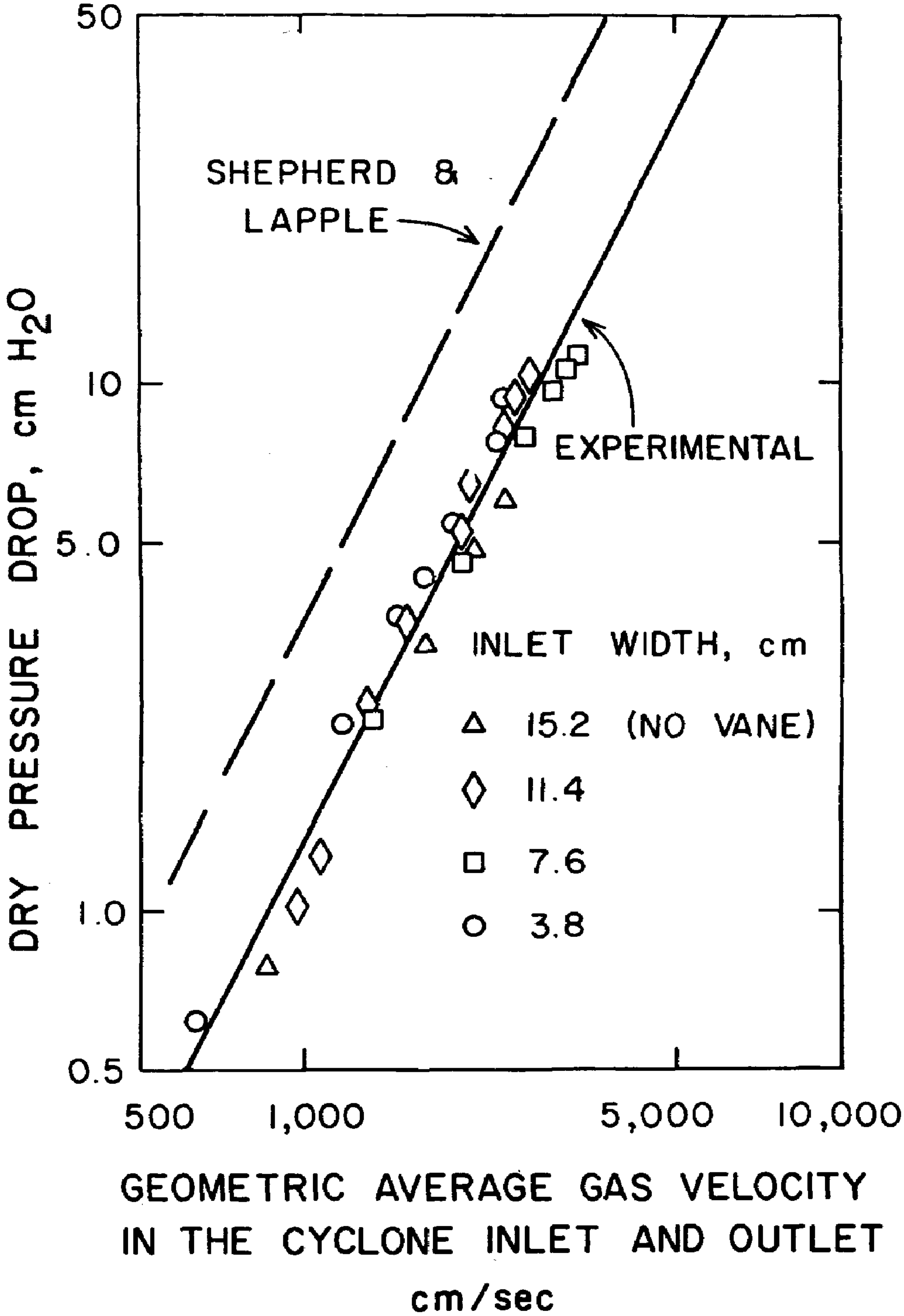


FIGURE 7

COMPARISON OF EXPERIMENTAL PRESSURE DROP DATA AND PREDICTED PRESSURE DROP FOR CYCLONE WITH INLET VANE BY SHEPHERD AND LAPPLE (1940).

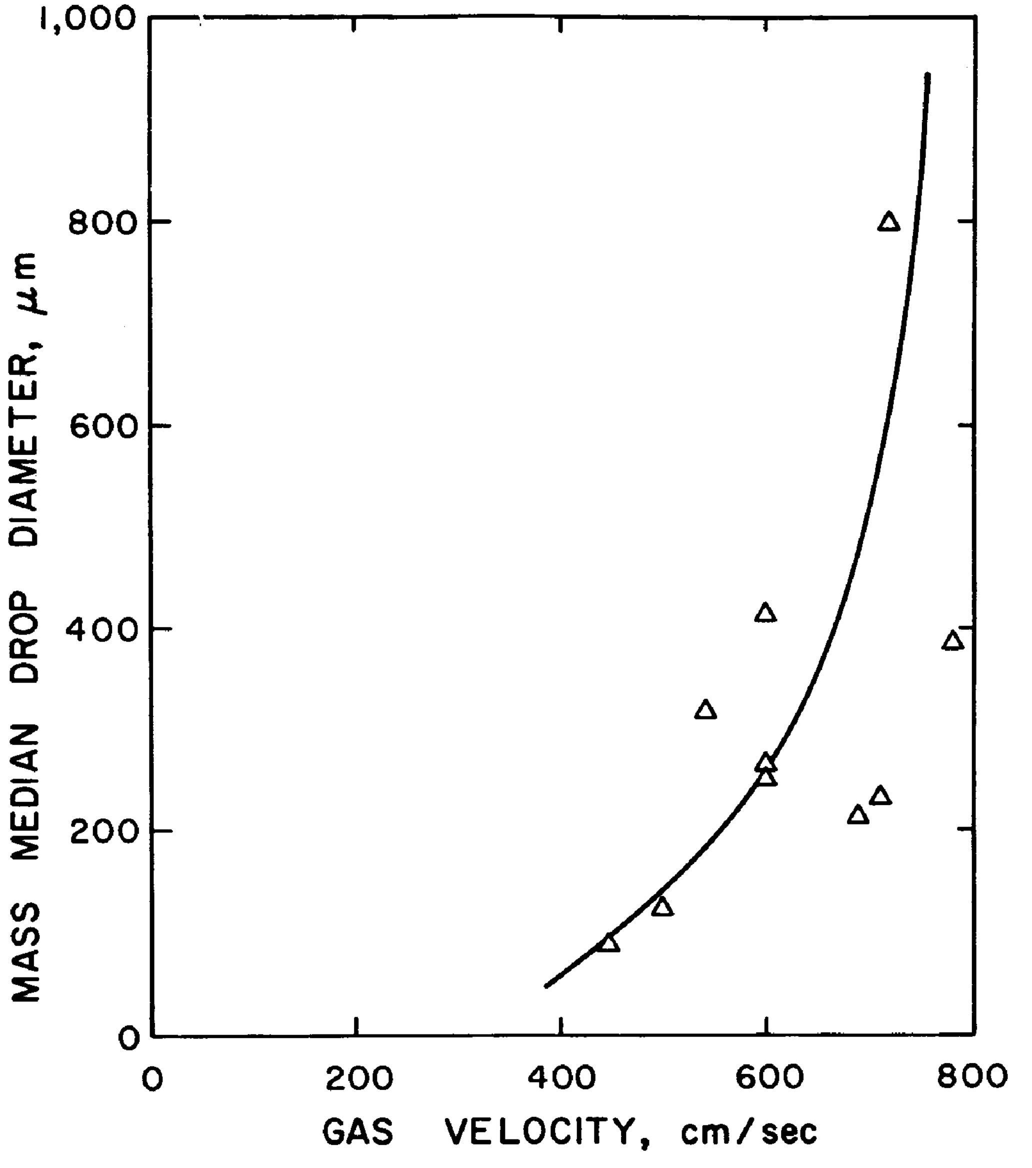


FIGURE 8

MASS MEDIAN OUTLET DROP DIAMETER FOR HORIZONTAL GAS FLOW IN KNITTED MESH. INLET d_{pg} = 82 μm.

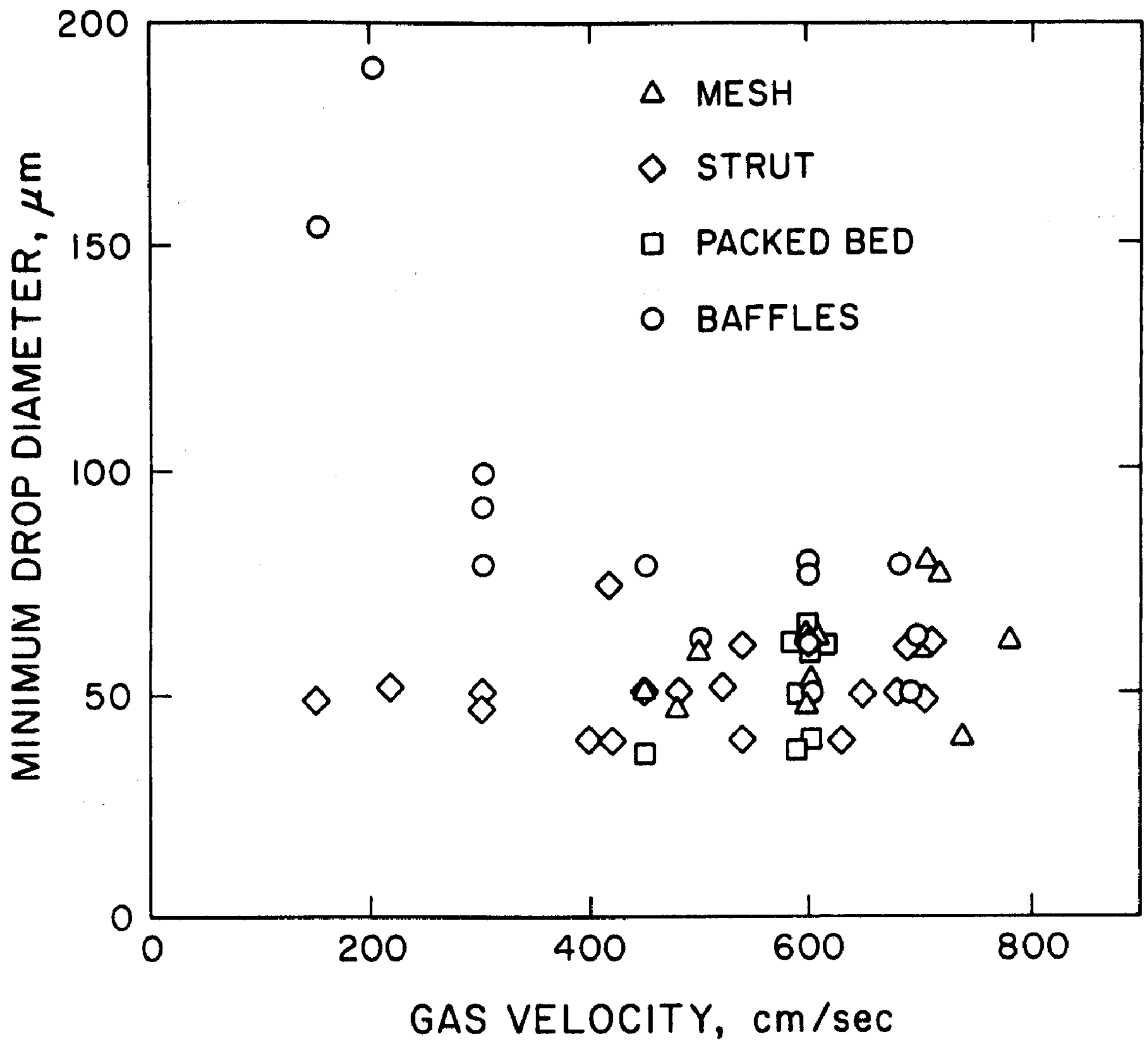


FIGURE 9

MINIMUM OUTLET DIAMETER VERSUS GAS VELOCITY

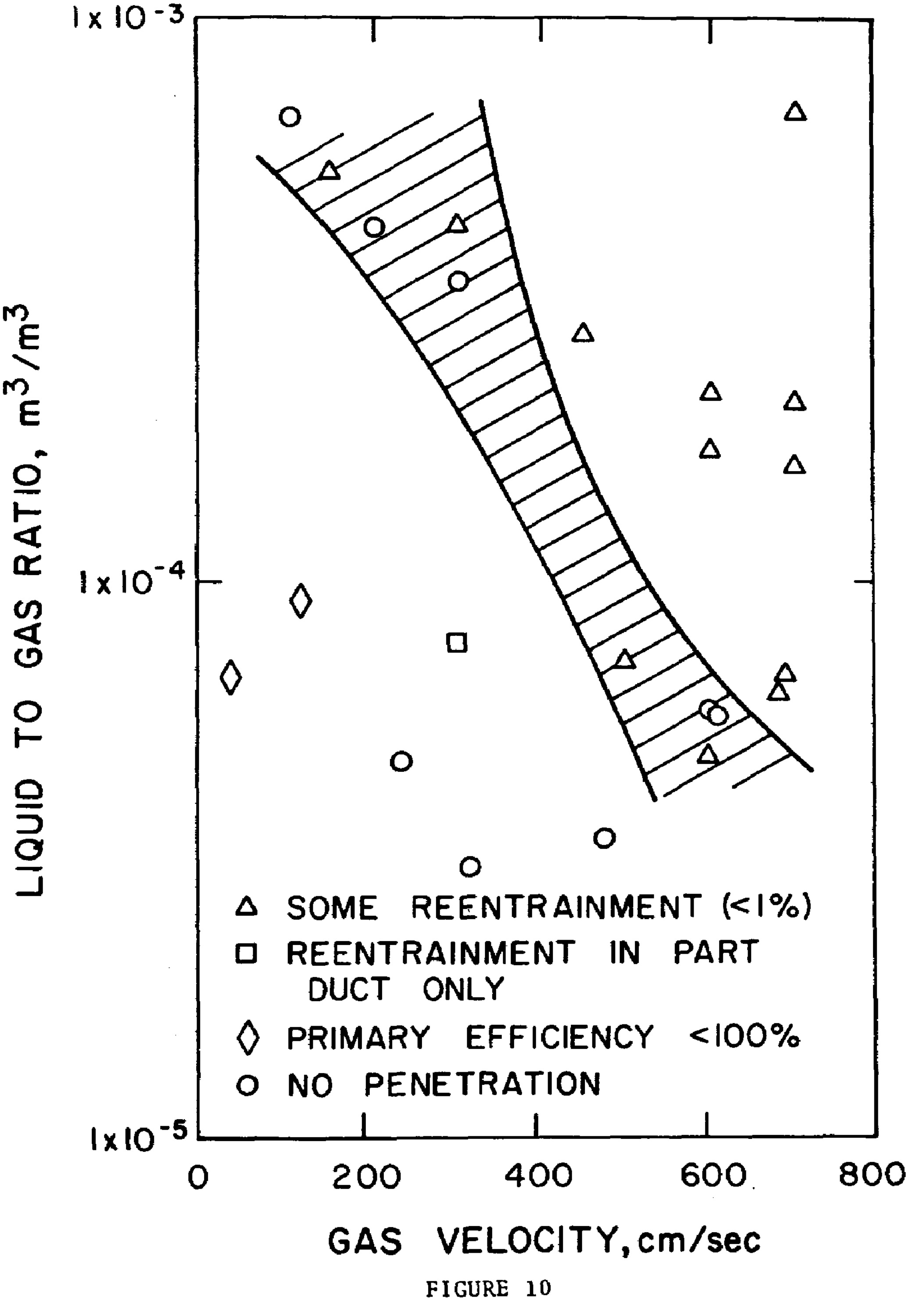


FIGURE 10

EFFECT OF GAS VELOCITY AND LIQUID LOAD ON REENTRAINMENT FROM BAFFLES.

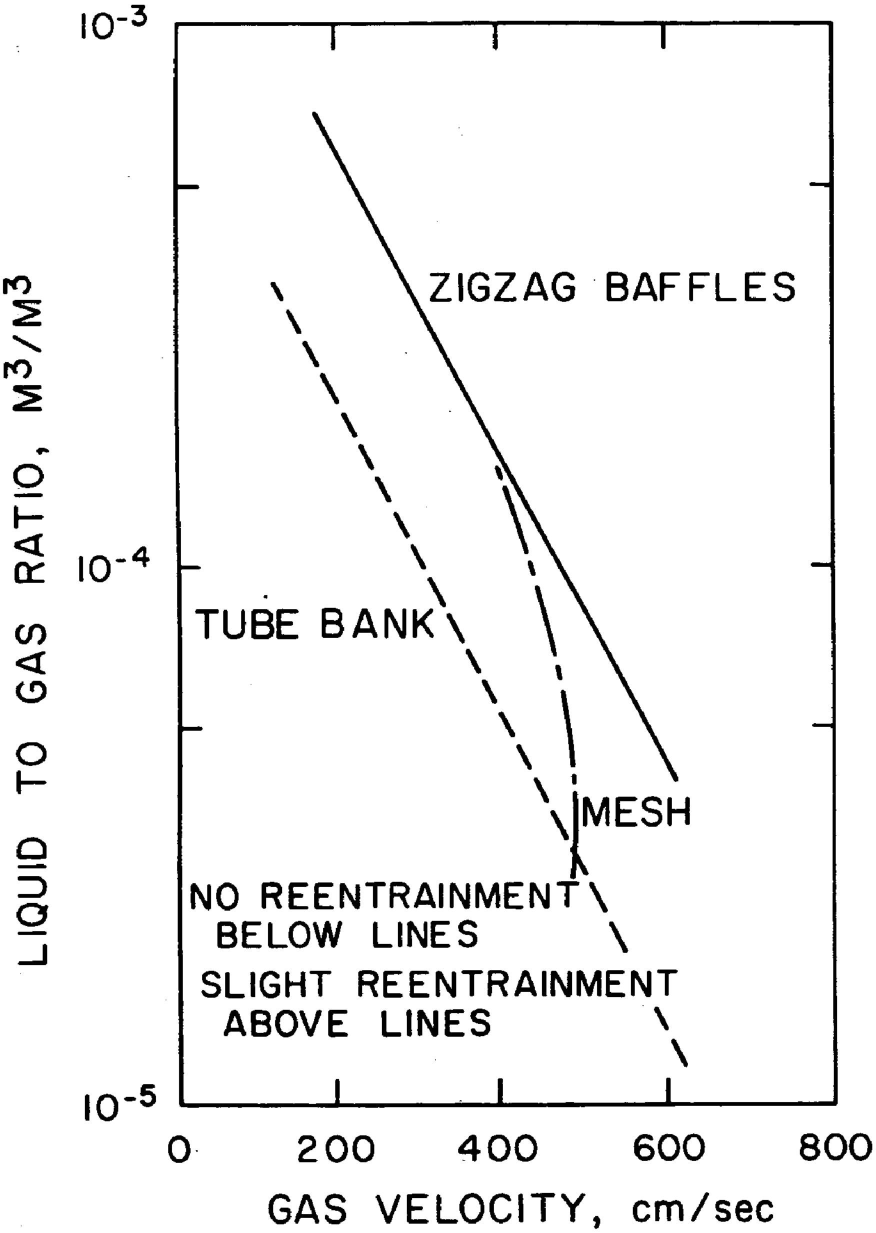


FIGURE 11

EXPERIMENTAL ONSET OF REENTRAINMENT CURVES FOR VARIOUS ENTRAINMENT SEPARATORS.

Future Needs for Fine Particle Scrubber Capabilities

by

Michael J. Pilat
Water and Air Resources Division
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The topic of future needs for fine particle scrubber capabilities can be addressed by posing two questions:

1. Are scrubbers needed for the control of fine particle emissions?
2. What are the research needs concerning fine particle scrubbers?

There are a number of cases where the use of wet scrubbers for fine particle control may be advantageous compared to electrostatic precipitators or filters. Some of the reasons for using wet scrubbers include:

1. Treatment of wet, corrosive, and/or explosive gases.
2. Simultaneous collection of particulate and gaseous pollutants.

Our overall objective concerning the development of fine particle scrubber technology should be to use theoretical and experimental studies to relate the scrubber particle efficiency as a function of particle size to the scrubber design and operating parameters. The scrubber design parameters include the geometry, dimensions, and locations of water sprays, inlets, and drains. The scrubber operating parameters include the gas pressure drop, water pressure drop, gas residence time, water/gas flow rate ratio, distance droplet travels with respect to the gas, depth of bubble froth, bubble size, distribution, droplet size distribution, gas velocity, water temperature, gas temperature, water vapor content, particle electrostatic charge/mass ratio, water electrostatic charge/mass ratio, and particle solubility in water.

In addition to pilot plant and full-scale scrubber studies, research is needed concerning scrubber particle collection mechanisms on a micro-scale, such as with single droplets (spray scrubbers) and single bubbles (sieve plates). The micro-scale studies should consider all the possible particle collecting mechanisms including inertial impaction, diffusiophoresis, thermophoresis, electrophoresis, magneto-phoresis, and Brownian diffusion. Also research is needed on particle-liquid interfacial phenomena (how particles reach when they impact upon the liquid surface; effects of wetting agents, electrostatic charges, particle solubility, etc.).

Good test methods and instrumentation are needed to measure the particle properties and the scrubber operating parameters. Parameters such as bubble size distribution, droplet size distribution, water electrostatic charge/mass ratio, particle electrostatic charge/mass ratio, etc. may have a significant effect upon the performance of fine particle scrubbers, yet these parameters are seldomly measured.

Scrubbers capable of collecting 99+% of fine (0.02 to 2 micron diameter) particles and having outlet particle concentrations in the 0.001 to 0.0001 grain/acf (2290 to 229 micrograms/m^3) range should be developed. Although such high particle collection efficiencies may not be needed in some cases, it would assist the construction and operation of reliable lower efficiency (say 95%) fine particle collection scrubbers if the 99+% fine particle collection efficiency scrubber technology was available.

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PANEL DISCUSSION

Moderator - Dr. Leslie E. Sparks

Panel Members -

Harold M. Haaland
Charles W. Lear
Robert C. Lorentz
James R. Martin
Jack E. Phelan
Alexander Weir, Jr.

Panel members gave brief introductory statements and then the floor was opened for questions from the audience. Those introductory statements which were available in written form at the time of printing are given below.

Harold M. Haaland
Western Precipitation Division
Joy Manufacturing Company

When we discuss the future of the collection of fine particulate from industrial gas streams I believe the first thing we must do is to unshackle our minds from the hardware concept of scrubbers, fabric filters, and electrostatic precipitators and concentrate on explaining the physical forces and mechanisms doing the work of separation.

The problem of air pollution by fine particulate is as old as time itself with naturally occurring fine particulate from volcanic action, sea water evaporation, and hydrocarbon release from forests. The industrial problem became great as soon as man created a high demand for metals at the start of the Industrial Revolution and smelters the world over volatilized and condensed as fine particulate tons of many metals. By 1896 we find Malvern W. Iles writing on "Methods for the Collection of Metallurgic Dust and Fume" in which he differentiates between common dust and "infinitely finer" fume. In that article he discusses deposition in long flues, filtering through porous media, use of water as drops, jets, and/or steam, use of static electricity, filtration through cloth and other methods. Then, and now, the real problems in evolving satisfactory engineering and hardware for industry were not in the area of ideas as to how to solve the problem; but rather how to solve the problem reasonably economically, using materials and techniques readily available.

The sound equipment designer must always maintain his position abreast of the state of the art and the better ones always maintain at least one probing effort out into the blue. The net result, in our area, is that most understanding and explanation of fundamentals has been preceded by empirically established equipment and a secondary effect has been to discourage fundamental research in industry as simply trying to explain what has already been done as opposed to what needs doing. This, of course, is poor reasoning as the cost of empirical experimentation and the price of failure go up astronomically in proportion to the degree of extrapolation from a sound fundamental data base.

On another tack, if we want to look for what has been done in the past as a guide to the future in very high efficiency particulate collection we must look at process gas cleaning rather than gas cleaning for air pollution purposes. This is due to the rigid requirements of some forms of process gas cleaning and the inherent payout on the equipment involved as compared to air pollution control work which has tended to only meet whatever regulations existed at any point in time.

Of these processes the cleaning of smelter gases for treatment in acid making plants and the treatment of blast furnace gases for use as auxiliary fuel probably represent the major flows of gases reduced to very low levels of particulate content. Other processes such as the cleaning of recirculating air in a long-submerged submarine can illustrate how far we can go but represent still more decades of cost increase and equipment complexity.

Both of the major gas stream examples illustrate the melding of process and equipment over a period of time to achieve the desired cleanliness goal. Both started with hot, dry dust collection equipment alone which served for a time but became obsolete as a demand for cleaner process gas evolved; and both switched to multiple collectors of varying types in series. Both are characterized in practice by being measured on final results largely by ad hoc plant methods based on visual and qualitative means.

The core elements to be derived from their experience and to serve as a guide to the future in fine particulate cleaning are:

(1) There is tremendous need for accurate, reliable instrumentation and techniques for the complete characterization of fine particulate in a quantitative way both physically and chemically.

(2) To achieve really fine cleaning of fine particulate from industrial gases a system approach must be used melding both approach process and cleaning equipment to get the optimum mix for any given application. It is doubtful that any one system will meet the needs of industry across the board.

(3) Even where a single piece of collection equipment appears capable of doing the cleaning job alternates should be considered to improve the long term life and reliability of the system; i.e. dry collectors before scrubbers to improve abrasive wear conditions, change chemical reaction conditions, or avoid plugging by dust surges.

(4) In many applications the cost of these next few steps toward ultra-cleaning are going to be extremely high; another order of magnitude over present costs. This is mandated by the avoidance of even the smallest of leakage paths, the widespread use of wet methods in various combinations with attendant corrosion and wet handling problems, and the sheer size of add-on equipment.

In conclusion, then, we can probably do the job that needs to be done but the tremendous costs likely to be imposed to achieve this end will demand the best the scientific and engineering communities can produce to accurately define the needs, the sources, and the measurement techniques in the fine particulate area.

Charles W. Lear
TRW Systems Group

Charged droplet scrubbing, like other scrubbing methods, is a means of removing particulate and fumes from dirty air through interactions of droplets of scrubbing liquor with the particles of dirt. Besides the normal impact and diffusional mechanisms, charged droplet scrubbing also includes electrical interactions. As the name implies, the scrubbing droplets, usually water, may carry an electrical charge and may move under the influence of electric fields. The particulate may also carry a charge other than its naturally occurring electric charge. The enhancement in droplet collection efficiency due to the electrical interactions make charged droplet scrubbing an attractive method for some applications involving particulate in the 0.1 to 1.0 micron size range.

In the TRW concept of charged droplet scrubbing, the scrubbing water is raised from ground to high voltage (about 40 kv) by flowing through a long electrical resistance path, which isolates with the electrical resistance of the water itself. The water is introduced into a hollow electrode which contains a series of hollow, elongated spray tubes. Emerging at the tips of these spray tubes, the water sees a high electric field force. Droplets are formed by the joint action of electrical and surface tension forces, in a classical electrohydrodynamic spraying process. Once formed, these droplets are highly charged, almost to the local breakdown limit or stability limit.

They move swiftly through the scrubbing volume under the influence of the electric field applied between the electrode and the collecting walls.

Because of the high droplet velocities (around 30 m/sec) induced by the ambient electric field, there is a large relative motion between droplets and particulate. This large relative motion enables the small particles to overcome aerodynamic forces which would normally sweep them around the droplet with the flow stream. Under inertial forces, they are able to approach the droplet more closely and interact. One such mode of interaction would be the familiar impact and agglomeration mode (electrically induced impact scrubbing).

If the particle passes close to the droplet but is not captured, it may still interact through a charge transfer from droplet to particle. The particle may become sufficiently highly charged to be precipitated within the scrubber. This mechanism is known as induced charging, and is important in the sub-micron size range.

In company research projects and in the present EPA funded program, mass removal efficiencies on the order of 60 percent per stage have been demonstrated on sub-micron particulates. Typical particulate distributions are newly dispersed iron oxide, or zinc oxide, each with estimated mass-mean-diameters on the order of one micron. A typical Charged-Droplet-Scrubber will consist of three stages with 95 percent efficiency or better.

Jack E. Phelan
Nalco Chemical Company

Case Histories on Application of Wet Scrubber Additives

Nalco Chemical Company is intensely involved in water treatment applications to the industries of this country. It is this background which has brought us into the wet gas scrubber field. We will now outline several case histories directly related to wet gas scrubbing.

Case History #1

The steel industry has found that the addition of No. 6 fuel oil or tar into the tuyeres of the blast furnace can partially replace some of the coke. However, this practice requires very close control, and slight deviations in application of oil produce unburned carbon, call it lamp black, carried out in the blast furnace gases. These gases are first passed through dry dust catchers and then through wet venturi type gas scrubbers. The solids picked up in the wet gas scrubber are sent to thickeners where they are precipitated and the water either sent to discharge or recycled. The solids are dewatered by vacuum filtration and reused in the sinter plant or land filled.

Recently we experienced in several plants, severe discharge problems of floating black particles going to the receiving streams. Severe foam conditions also existed on top of the clarifying equipment. This problem caused the plants to cut back on their fuel injection.

Initially we recommended better firing practices for the fuel. Then we screened a number of experimental chemical products and found that two products working together had the ability of wetting the carbon black and keeping the venturis clean without interfering with the settling rate of the clarification system. This program was an immediate success and has been in operation approximately nine months. It has also allowed the plant to increase fuel oil injection.

Further work yielded a single product to provide the following benefits in a variety of wet scrubber applications.

a) no lamp black problem on clarifiers
b) improved removal of particulate matter in gases going to combustion areas
c) increased suspended solids in water going to thickener, indicating good deposit control
d) cleaner operation of burner equipment utilizing blast furnace gas

Case History #2

A large midwest gray iron foundry was experiencing severe fouling of their packed wet gas scrubber equipment. This was resulting in down time cleaning, once every three weeks, plus giving the plant opacity problems. The plant stacks were reading 40-45% and citations were being given. A major expenditure of around $1,000,000 was being worked up to correct this condition.

A trial run was made on one of the scrubber systems during the last week of a three week cycle to see what effect a dirty system would make. After one week, the system was shut down to inspect. The normally very dirty rings were only slightly fouled and the opacity had improved.

After a full three week program we found the equipment practically as clean as when we started and also found the opacity had decreased to the range of 20 to 25%, meeting the standards required.

Four times in the next six months we were called by the plant to check out increasing opacity readings. Each time we found the mechanical feeding equipment had been shut off and after placing it back in service, had the opacity readings go back to the range of 20 to 25%. Permanent installation of feedings equipment is now installed so that supervisory personnel can monitor the equipment daily.

Case History #3

A large Eastern Steel Mill has a wet scrubbing B.O.F. operation and has been successfully fulfilling their emission standard readings. Their opacity readings are constantly around ten percent and their grains per standard cubic foot are within regulatory legislation.

However, during the warmer months they show a small amount of fine red coloring in the emission stack. In a current evaluation at this plant our findings to date show us a decrease in particulate matter ranging from 20 to 25%. Further work is being done in this area.

Conclusions

The normally very efficient wet scrubbers manufactured by many corporations, can show improved performance by controlled chemical treatment of the wet scrubber water. These improvements can be -

a) dispersion of solids
b) improved wetting of particulate
c) maintaining clean nozzles and flooded surfaces
d) control of deposits
e) preventing corrosion and clogging with corrosion products
f) de-tackifying "sticky" dispersions

Data from successful applications shows that chemical treatment can mean the difference between compliance with regulations on air emissions or citation for failure to comply. But success also requires close surveillance of the water chemistry of the system for such basic control parameters as pH, TDS, suspended solids, hardness, alkalinity and additive dosage.

Dr. Alexander Weir, Jr.
Southern California Edison Company

Theee has been considerable discussion of the removal of particles under 2 microns in the symposium, but since the first of this year our company at the Mojave Generating Station had removed about 83 tons of particles under 2 microns with one scrubber. When the cost of the scrubber was prorated over this removal, it appeared that we spent about $100,000 a ton removing these particles and one might question whether the cost was worth the benefit. The scrubber was operated primarily to remove sulfur dioxide and the inlet concentration of sulfur dioxide to the scrubber (around 200 ppm) was lower than the exit concentration of sulfur dioxide achieved in the EPA scrubber program at Shawnee.

There is a contention that the presence of fine particles resulted in a reduction of visibility but in the Los Angeles Basin that the visibility reduction is probably due primarily to the formation of photochemical smog, most of which was due to emissions of the NO_x and hydrocarbon vapor from automobiles. Whatever the automobile's contribution of NO_x, it is generally accepted that in Los Angeles visibility reduction is not due to emissions from power plants.

Our experience supports the view that scaling up particulate removal data from pilot plants to full size scrubbers is in fact very difficult.

Closing Comments
by
D. C. Drehmel

Fine particles are those which penetrate into the respiratory system where they may act as a carcinogen, may contribute to blockage of the alveoli, or may accommodate pulmonary pathogens. Mr. Harrington observed that fine particles are not a single pollutant but a large category of pollutants. It is therefore difficult to agree on a general definition of fine particles as a pollutant. However, it has been shown that particles with diameters smaller than 5 micrometers do penetrate past the nasal cavity and nasopharynx into the lungs and that particles with diameters as small as 0.01 micrometers are deposited in the lungs. Other problems associated with submicron particles are that they are slow in settling out of the atmosphere and they create haze and adverse weather modification.

Scrubbers have a significant role to play in the control of fine particle emissions from stationary sources. As already noted by Dr. Pilat, scrubbers will be necessary for simultaneous collection of gaseous and particulate emissions and for the collection of particulate in the presence of wet, corrosive or explosive gases. Furthermore, scrubbers may be necessary for the control of particles which have properties unsuitable for the operation of alternative control devices; for example, a particulate with poor cake release properties in a fabric filter.

The ability of conventional scrubbers to control fine particles was discussed by several authors (Beeckmans, Calvert, Eckert, and Hesketh). For particles in the 1 to 5 (and above) micrometer range, impaction is the important mechanism and in the 0.01 to 0.1 micrometer range, diffusion is the important mechanism. Control of particulate emissions in these regions is highly efficient when the effect of the appropriate collection mechanism is optimized. The use of special designs or new concepts to capture fine particles was the subject of most of the authors (Gardenier, Jhaveri, Sparks, Leith, and Rich). Even in the particle size region where both the diffusion and impaction mechanisms are least effective, these authors have shown that scrubbers can be highly effective in collecting fine particles.

It was the intent of the Control Systems Laboratory of EPA in sponsoring this symposium to stimulate the development of new concepts for the control of fine particulate emissions. New concepts discussed at the symposium verify not only that the development of scrubbers is important to the solution of the air quality problem but also that new scrubber concepts are a first step to controlling fine particulate emissions in all size ranges.

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16. ABSTRACT These proceedings contain the 14 papers presented during the symposium, which emphasized the collection of fine particles (solid or liquid particles smaller than about 3 microns) by any type of wet collector, including hybrid devices. The objective of the symposium was to stimulate and generate new and novel ideas for controlling fine particulate emitted from stationary sources and promote interchange of ideas among scrubber experts. The consensus of the symposium was that scrubbers have a significant role to play in controlling fine particulate. Several papers discussed the ability of conventional scrubbers to control fine particles. Most of the papers dealt with the use of special designs or new concepts to capture fine particles. Symposium attendees concluded that not only is scrubber development important to the solution of the air quality problem, but that new scrubber concepts are a first step to controlling particulate emissions in all size ranges.

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