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OVERVIEW OF EPA/IERL-RTP SCRUBBER PROGRAMS

Industrial Environmental Research Laboratory
Office of Research and Development
U.S. Environmental Protection Agency
Research Triangle Park, N.C. 27711

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OVERVIEW OF
EPA/IERL-RTP
SCRUBBER PROGRAMS

by

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The direction and content of this work was strongly influenced by the guidance and assistance of the Project Officer, Dr. Leslie E. Sparks, Industrial Environmental Research Laboratory - Research Triangle Park (IERL-RTP), of the Environmental Protection Agency, Research Triangle Park, North Carolina, to whom we extend our thanks.

SECTION I

CONCLUSIONS

This report is descriptive rather than evaluative, and no conclusions have been formulated.

SECTION II

RECOMMENDATIONS

No recommendations are presented because this report is descriptive rather than evaluative.

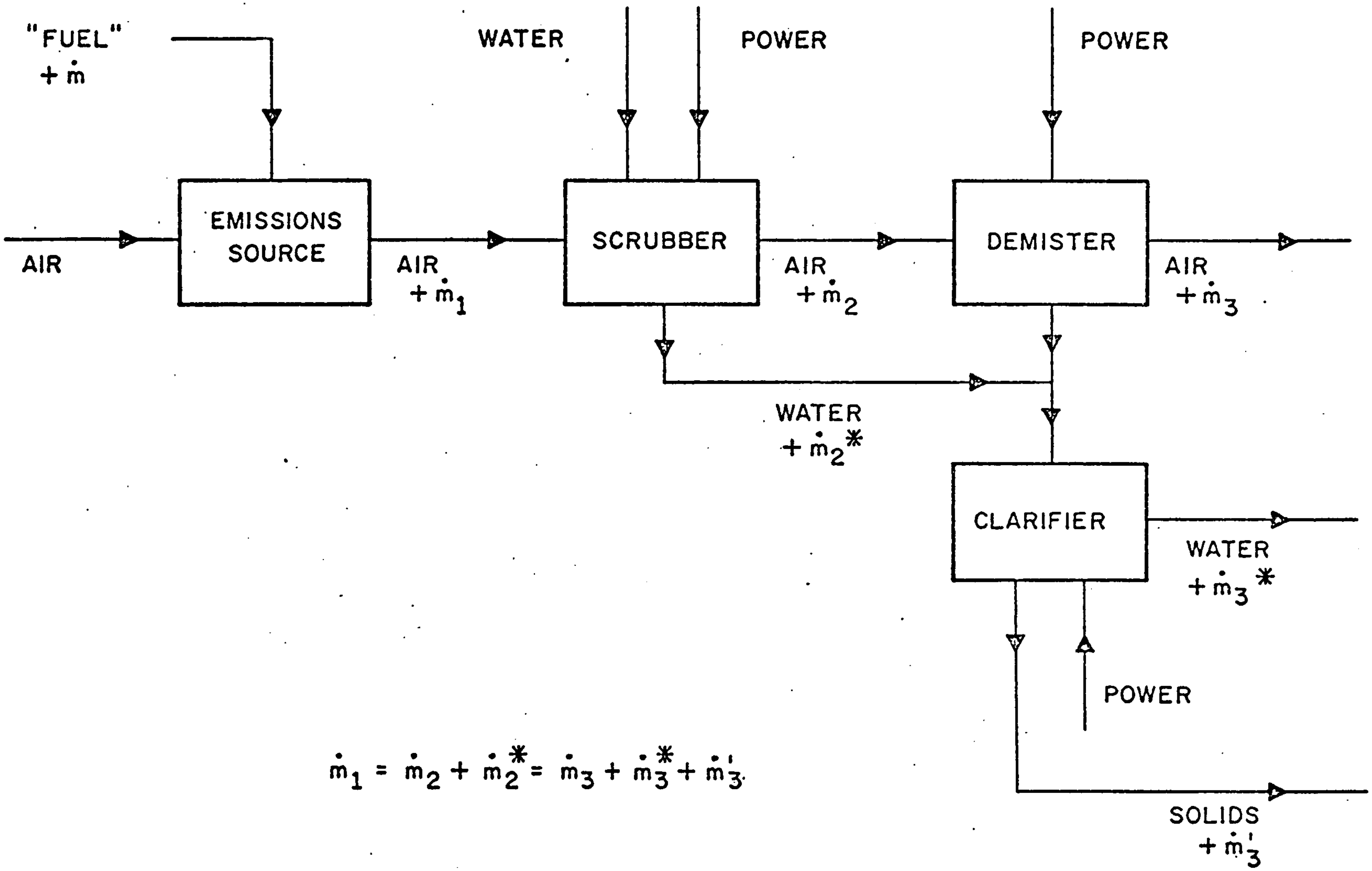
SECTION III

INTRODUCTION

In this section we present an introduction to the particulate scrubbing programs sponsored by the Industrial Environmental Research Laboratory-Research Triangle Park of the U.S. Environmental Protection Agency (EPA). The components of a particulate pollutant scrubber system are briefly described, as an aid to the understanding of the short discussion of the status of the Industrial Environmental Research Laboratory-Research Triangle Park scrubber programs which follows. Finally, a tabular presentation is made of all the IERL-RTP scrubber programs. Section IV shows the interrelations between the scrubber programs on a topic-by-topic basis, serving also as a review of the state of the art. Section V describes the chronological development of the scrubber program, highlighting the reasons behind that evolution.

DESCRIPTION OF GENERALIZED SCRUBBER SYSTEM

Figure 1 is a schematic of a scrubber system. An emissions source produces airborne pollutants at the mass rate of $\dot{m}_1$, described in units such as pounds per hour or kg/s. The scrubber uses water and power to remove some of the pollutant material from the air; conservation of mass requires that at steady state the air-borne mass emission rate downstream from the scrubber, $\dot{m}_2$, and the water-borne mass emission rate, $\dot{m}_2^*$, will equal the mass rate into the scrubber, $\dot{m}_1$. The air from the scrubber will usually have water droplets entrained with it; a demister (entrainment separator) will be used to remove these droplets and whatever pollutant mass they carry with them, leaving an air flow with a



$$\dot{m}_1 = \dot{m}_2 + \dot{m}_2^* = \dot{m}_3 + \dot{m}_3^* + \dot{m}_3'$$

Figure 1. Generalized description of scrubber system

mass rate of emissions $\dot{m}_3$. The collection efficiency of the scrubber plus demister would then be $1 - \dot{m}_3/\dot{m}_1$ on a mass basis. The water from the scrubber will contain captured material; generally it will be pumped to a clarifying system which will use power to remove some of the particulate material as solid waste (with a mass rate $\dot{m}_3'$). The water leaves the clarifier with a mass rate of water-borne emissions $\dot{m}_3^*$. Mass conservation means that the pollutants generated will leave the scrubber as gases, liquids or solids either air-borne, liquid-borne or solid-borne.

As for clarifiers and their effluents, IERL-RTP has sponsored a 4-year study of environmental acceptability and economics of techniques for treating the sludge from scrubbing methods of flue gas desulfurization, with a final report due this year. This is not discussed further in this document, as the research is more related to gas scrubbing than to fine particulate scrubbing and the amount of solid material to be treated in flue gas desulfurization will differ greatly from that encountered in most particulate scrubbing contexts.

IMPORTANCE OF SCRUBBERS

Scrubbers have certain advantages as particle control devices: They often collect both particles and gases. Gas temperatures are reduced by evaporation. The explosive characteristics of certain dusts may be quenched by the scrubber moisture. Finally, scrubbers are usually more compact than fabric filter or electrostatic precipitator installations of comparable volume flow rate capacity.[1]

Midwest Research Institute (MRI) in its document, Particulate Pollutant System Study,[2] ranked the sources of particulate emissions. The Industrial Environmental Research Laboratory-Research Triangle Park staff has identified the kinds of scrubbers used, if any, in the MRI list of major source categories, an abridged version of which appears here as Table 1. The top 10 source types are listed along with scrubbers employed by installations in the industry. Nine of the 10 most significant

Table 1. TEN LARGEST SOURCES OF PARTICULATES AND SCRUBBER SYSTEMS USED, IF ANY

Source type	Scrubber type					
	High energy[b]	Moderate energy[c]	Low energy[d]	Novel	Flux force	Charged droplet
Crushed stone			x			
Coal combustion (electrical utility)			x			
Basic oxygen furnace (steel)	x				x	
Kraft pulp recovery furnace	x					x
Cement rotary kiln						
Hot-mix asphalt dryer			x	x		x
Ferroalloy electric furnace	x			x	x	
Open hearth furnace (steel)	x			x		
Coal combustion (industrial)			x			
Lime plants, rotary kilns	x					

[a] Ranked according to MRI Study, Particulate Pollutant System Study, (Table 7, Vol. 2)

[b] ~ 250 cm H_2O or ~ 15 hp/1000 acfm or $\sim 25 \times 10^3$ N/m^2

[c] ~ 60 cm H_2O or ~ 3 hp/1000 acfm or $\sim 60 \times 10^2$ N/m^2

[d] ~ 20 cm H_2O or ~ 1 hp/1000 acfm or $\sim 25 \times 10^2$ N/m^2

sources have installations using scrubbers. Nine of the 10 next most significant sources also employ scrubbers of one type or another. Clearly, scrubber technology has an important position in particulate pollution control.

DESCRIPTION OF IERL-RTP SCRUBBER STUDIES

Objective

The broad objective of the fine particle scrubber program is the development of energy-efficient and cost-efficient scrubber systems for fine particle control. For various industries, scrubbers have been found to be the cost-effective control technology. Put into quantitative terms: the objective is to develop a scrubber with power consumption per volume flow equivalent to 30-50 cm WC (12-20 in. H_2O) pressure drop capable of collecting at least 90 percent by mass of particles having aerodynamic diameters ≤ 1 μm.

State of the Art

Figure 2 is adapted from a paper by Calvert[3] which in turn is partially based on results presented in the Scrubber Handbook.[4] It shows the cut diameter of the scrubber system plotted against its actual pressure drop, its hydraulic power consumption per unit volume of air flow. Hydraulic power is volume flow rate times pressure drop. Calvert showed how total efficiency can also be obtained from scrubber cut diameter and aerosol size parameters.[3] The cut diameter is the particle aerodynamic diameter for which the scrubber collection efficiency is 50 percent. This can be obtained from data on scrubber collection efficiency versus particle aerodynamic diameter. (The particle aerodynamic diameter is the diameter of a spherical particle of unit density that has the same settling velocity.) The figure shows sieve plate, impingement plate, and packed scrubber characteristics as well as curves for venturi scrubbers under a variety of conditions (denoted by different empirical curve

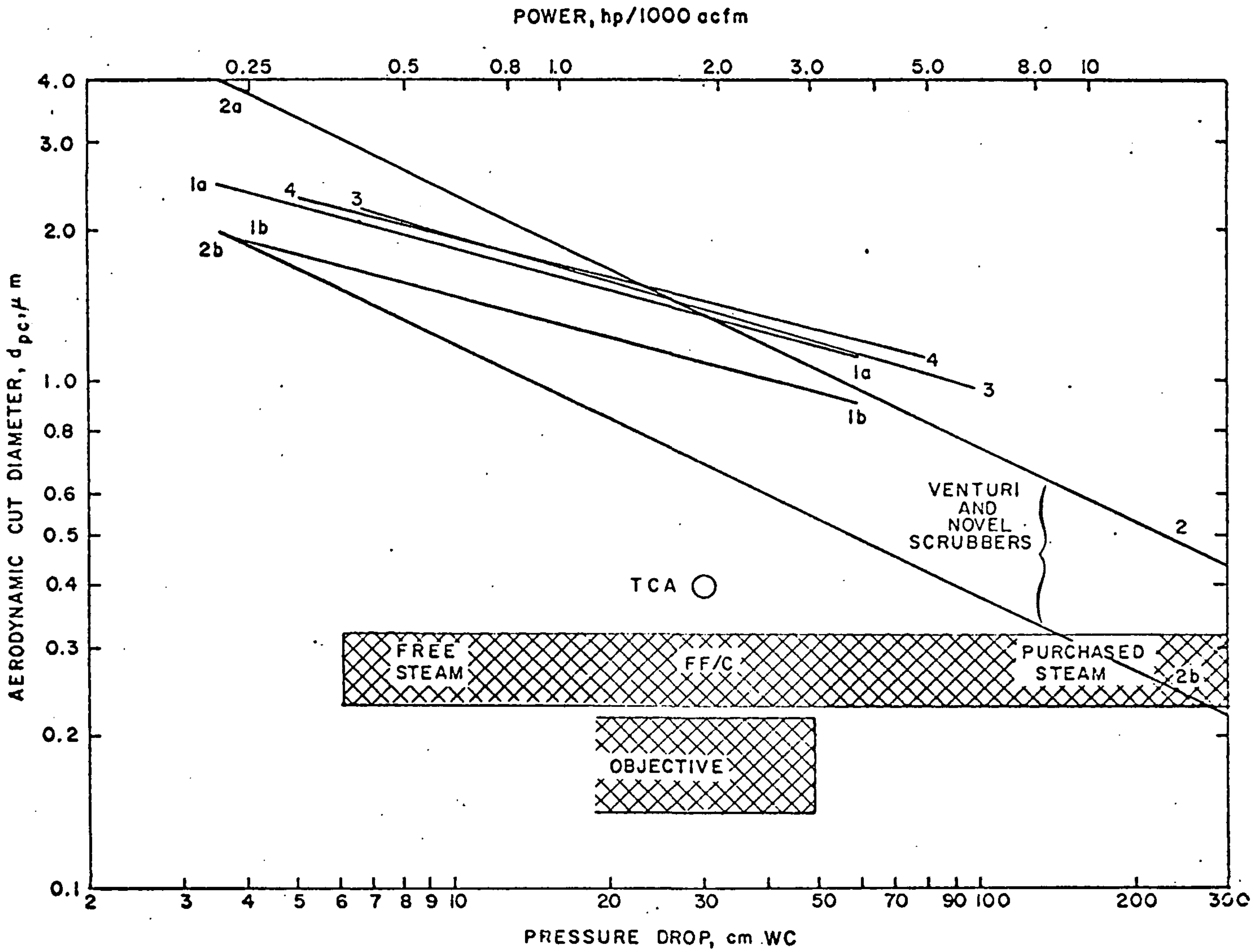


Figure 2. Predicted aerodynamic cut diameter versus pressure drop and power consumption (adapted from Scrubber Handbook).[4] Lines 1a and 1b are for sieve plates; line 3 is for impingement plate; line 4 is for a packed column; lines 2a and 2b are for venturi scrubbers with f = 0.25, 0.50 respectively. See text.

fitting factors, f). With the exception of two TCA (Turbulent Contacting Absorber) scrubbers, the novel scrubbers tested by Industrial Environmental Research Laboratory-Research Triangle Park can be represented by points along or above the line 2b (f = 0.5) for venturi scrubbers. The TCA scrubbers are represented by the circle labeled TCA. Agreement between scrubber theory and experimental evaluation shows that inertial impaction is at present the primary collection mechanism at work. To improve scrubbers dramatically, new forces will need to be introduced into the scrubbing process or the fine particles will have to be grown to a size where they can be caught inertially.

Status of the IERL-RTP Program

The major thrust of the IERL-RTP's scrubber program has been aimed at developing and demonstrating Flux Force/Condensation (FF/C) Scrubbers. In an FF/C scrubber, water vapor is condensed in the scrubber. When the water vapor condenses, additional forces and particle growth contribute to the particle collection process. When the water vapor or steam is "free," FF/C scrubbers are low energy users. However, when waste heat is not available, FF/C scrubbers require additional energy inputs for efficient particle collection. A rough idea of the energy consumption/performance relationship for FF/C scrubbers is shown in Figure 2. The left hand region of the FF/C regime is for free steam and the right hand region is for purchased steam. Note that when steam is free FF/C scrubbers approach the program objective. The questions of how much steam is needed and how much is free are major unknowns at present. The answers to both questions are likely to be source-specific. Thus, pilot demonstrations on a variety of sources are necessary to provide the required data. A pilot demonstration is underway and an additional one is planned for FY76.

With two possible exceptions, performance data for all the non-FF/C scrubbers (i.e., all conventional and novel scrubber work) confirm

Figure 2. The first possible exception came out of the "Wet Scrubber Liquid Utilization" program at Stanford Research Institute.[5] This research indicated that a series of low-energy, low-efficiency scrubbers might achieve much higher total efficiency at a given energy consumption than could a single high energy scrubber, allowing a trade-off between capital costs and operating costs. This lead, plus final confirmation of Figure 2, will be followed up in research funded in FY75.

The other possible exception to Figure 2 is the TCA or mobile bed scrubber. Data from field tests of TCA scrubbers are shown in Figure 2. Note that the TCA point is below the venturi and other scrubber lines by a significant amount (TCA cut diameter is about one-half that of a venturi at similar power consumption). At present there is no explanation for the observed performance of these mobile bed scrubbers. In fact, one scrubber vendor claims that mobile bed scrubbers (single-stage or multi-stage) are less efficient than venturi scrubbers. An FY75 program will seek the explanation for the observed performance and design equations and theoretical models for mobile bed scrubbers. FY76 funds will be used to investigate effects of slurry scrubbing in mobile bed scrubber performance. Pilot plant work will be coordinated with the full-scale tests at the Shawnee Wet Limestone Scrubbing Test Facility, a coal-fired boiler instrumented for research into flue gas desulfurization at realistic flow rates (e.g.,20,000 acfm, 10 m^3/s).

The overall efficiency of a scrubber system is determined by the efficiency of the scrubber and the efficiency of the entrainment separator. Recent field data indicate that in some cases inefficient entrainment separator operation is a major cause of poor collection of fine particles by scrubbers. IERL-RTP has nearly completed a systematic study of entrainment separators. FY76 funds are provided to develop and demonstrate, in cooperation with SO_x scrubbing research and development, efficient and trouble-free entrainment separators.

We close this section with two tables. Table 2 lists the scrubber projects sponsored by IERL-RTP, listed in order of starting date. Table 3 gives publications available from NTIS concerning IERL-RTP work in scrubber technology. (Order from: National Technical Information Service, U.S. Department of Commerce, Springfield, Virginia 22151). Next, in Section IV, the major themes of the IERL-RTP work are discussed. In Section V is presented a chronological overview of the IERL-RTP programs concerning particulate scrubbing technology.

Table 2. LIST OF PROJECTS RELATED TO SCRUBBER RESEARCH AND DEVELOPMENT SPONSORED BY INDUSTRIAL ENVIRONMENTAL RESEARCH LABORATORY-RESEARCH TRIANGLE PARK (IERL-RTP)

Starting date	Title
1970	Wet Scrubber Systems Study
	Flux Force/Condensation Scrubber Feasibility
	Fine Particle Scrubber Performance Tests
1971	Systems of Charged Droplets and Electric Fields for the Removal of Submicron Particulates
September 1972	Wet Scrubber Entrainment Separation
December 1972	Pilot Scale Demonstration of Charged Droplet Scrubbing
June 1973	Wet Scrubber Development II (FF/C Scrubbers)
September 1973	Wet Scrubber Liquid Utilization
September 1973	Design and Fabrication of Mobile Wet Scrubber Facility
October 1973	Foam Scrubbing for Fine Particle Control
December 1973	Growth of Fine Particles by Condensation
June 1974	Fine Particle Collection with University of Washington Electrostatic Scrubber
1974	Evaluation of Novel Control Devices
June 1974	FF/C Scrubber Pilot Plant
July 1974	Evaluation of Wet Scrubbers for Control of Particulate Emissions from Utility Boilers
July 1974	Operation of EPA-Owned Mobile Units, Aerodynamic Test Chamber, and Pilot Scrubbers
August 1974	Rocket Motor Emissions Control
September 1974	Entrainment Characteristics of Mobile Bed Scrubbers
January 1975	Evaluation of Horizontal Scrubber
February 1975	Evaluation of Systems for Control of Rocket Motor Test Pad Emissions
April 1975	Evaluation of Electrostatic Scrubber
Proposed	Effects of Interfacial Properties on Fine Particle Scrubbing
Proposed	Mobile Bed FF/C Scrubbers for Collection of Fine Particles
Proposed	Wet Scrubber Energy Utilization

Table 3. PUBLICATIONS AVAILABLE FROM NTIS RELATED TO IERL-RTP SPONSORED WORK IN SCRUBBER TECHNOLOGY

Novel devices

Contractor (contract number)	NTIS number	Report title and date
Southern Research Institute for M.W. Kellog (68-02-1308)	PB 232-436/AS EPA-650/2-74-028	Lone Star Steel Steam-Hydro Air Cleaning System Evaluation (Task 11)--4/74
GCA (68-02-1316)	PB 234-146/AS EPA-650/2-74-036	Braxton Sonic Agglomerator Evaluation (Task 1)--5/75
Southern Research Institute	PB 239-422/AS EPA-650/2-74-129	Evaluation of Aronetics Two-Phase Jet Scrubber--12/74
GCA (68-02-1487)	PB 240-397/AS EPA-650/2-75-024-a	Pentapure Impinger Evaluation--3/75

New concepts

Contractor (contract number)	NTIS number	Report title and date
MIT (68-02-0018)	PB 205-188 (APTD 0869)	Electrical Induction of Particulate Agglomeration (Final Report, Task Order 7)--8/71
	PB 205-187 (APTD 0868)	Charged Droplet Technology for Removal of Particulates from Industrial Gases (Final Report, Task Order 8)--8/71
CSL	PB 236-676/AS EPA-650/2-74/081	Seminar on Electrostatics and Fine Particles, September 1973--8/74

Wet scrubbers

Contractor (contract number)	NTIS number	Report title and date
Ambient Purification Technology (CPA 70-95)	PB 213-016 EPA-R2-72-118a	Wet Scrubber Systems Study, (Handbook) Vol. I--8/72
	PB 213-017 EPA-R2-72-118b	Same Vol. II-8/72 (Final report & Bibliography)
APT	PB 227-307 EPA-650/2-73-036	Feasibility of Flux Force/Condensation Scrubbing for Fine Particulate Collection--10/73

Table 3 (continued). PUBLICATIONS AVAILABLE FROM NTIS RELATED TO IERL-RTP SPONSORED WORK IN SCRUBBER TECHNOLOGY

Wet scrubbers		
Contractor (contract number)	NTIS number	Report title and date
APT, Inc. (68-02-1328)	PB 239-335/AS EPA-650/2-74-112	EPA Fine Particle Scrubber Symposium (San Diego, 5/74)--10/74
APT, Inc. (68-02-0637)	PB Not assigned EPA-650/2-74-119-a	Entrainment Separators for Scrubbers-Initial Report--10/74
APT, Inc.	PB-240-235/AS EPA-650/2-74-093	Fine Particle Scrubber Performance Tests--10/74
Stanford Research Institute (68-02-1079)	PB 237-749/AS EPA-650/2-74-108	Wet Scrubber Liquid Utilization--10/74

SECTION IV

TOPICAL OVERVIEW

INTRODUCTION

In general terms, the work of the Industrial Environmental Research Laboratory-Research Triangle Park in scrubber technology has focused on understanding the operation of scrubbers and using that understanding to improve their performance as fine particle control devices. A review of scrubber technology under IERL-RTP sponsorship produced the Scrubber Handbook written by Calvert and co-workers at APT, Inc.[4] The models presented there have been generally borne out by experimental work performed on scrubbers by IERL-RTP contractors and others. As noted in the preceeding section, efficiency versus power consumption has been found to be quite similar for conventional scrubber types, with two interesting exceptions, low-energy scrubbers in series and TCA mobile-bed scrubbers. Unconventional approaches, specifically flux force/condensation scrubbing and electrostatic scrubbing, also produce high efficiencies at atypically low power consumptions. In this section we describe the operation of a spray scrubber in terms of a simple model to indicate the promise of these two unconventional approaches. After a discussion of FF/C and electrostatic scrubbing investigations, two other subjects are focused on: demisting (entrainment separation) and interfacial effects between particle and scrubber liquid, both potentially important obstacles to high efficiency scrubbing.

GENERAL COLLECTION MODEL

An approximate general formula for collection of particles of diameter d_p by scrubbers (and electrostatic precipitators) can be shown to be:

$$Pt = n/n_o = \exp\ (-\ w\ A/Q) \tag{1}$$

where: n/n_o = penetration, one minus the efficiency (1 - E)

n = outlet number concentration;

n_o = inlet number concentration;

w = net particle velocity toward collecting surface, the migration velocity;

A = total collection surface area;

Q = gas volume flow rate.

(This equation applies to a single particle size. For polydisperse aerosols, the equation should be integrated over the particle size distribution.) Collection efficiencies are high when the magnitude of the argument of the exponent is large. The migration velocity will depend upon the collection mechanisms. For collection due to inertial impaction, which depends on the inability of particles (due to their inertia) to follow the flow streamlines around an obstacle such as a scrubber droplet, the migration velocity is given by:

$$w = \eta\ (u_p - u_d)\ A_d/A \tag{2}$$

where: η = single droplet collection efficiency;

u_p = particle velocity;

u_d = droplet velocity;

A_d = droplet cross-sectional area.

Particles in a moving stream will impact upon a perpendicular surface provided that the inertia of the particles is sufficient to overcome the drag exerted by the air stream deflected by the impaction surface. The impaction process can be characterized by the impaction parameter ψ which is defined by the following expression:

$$\psi = \frac{C \rho_p v d_p^2}{18 \mu D} \tag{3}$$

where: ρ_p = particle density;
v = gas velocity;
d_p = particle diameter;
μ = gas viscosity;
D = obstacle diameter;
C = Cunningham correction factor defined empirically as:

$$C = 1 + 2.492 \lambda/d_p + 0.84 \lambda/d_p \exp(-0.435 d_p/\lambda);$$

where: λ is the molecular mean free path.

Various functions of the impaction parameter have been found, empirically, to approximate the single droplet efficiency for impaction on spheres. As the impaction parameter increases, so does collection efficiency.

In the <u>Scrubber Handbook</u>,[4] the following equation is derived to correlate fractional penetration, with pressure drop, ΔP, in spray scrubbers:

$$n/n_o = P_t = \exp\left(- \frac{0.61 \left(C \rho_p d_p^2\right) \Delta P f^2 \rho_L}{\mu^2}\right) \tag{4}$$

where: ΔP = pressure drop, cm WC
ρ_L = scrubbing liquid density, g/cm^3
μ = gas viscosity, poise

(The parameter f is determined empirically; it includes effects such as mean droplet/gas relative velocity, particle wettability, and venturi throat liquid distribution. Usually f is between 0.5 and 0.25.)

Figure 3 shows how strongly penetration depends upon particle diameter and venturi pressure drop, based upon equation (4). For a given particle size the penetration decreases rapidly with increased pressure drop. For a given pressure drop, the penetration decreases even more rapidly as particle size increases.

The collection efficiency curves in Figure 2 and 3 have generally been borne out by experimental data obtained on conventional scrubbers and novel scrubber types. The agreement serves as support for equation (4) and analogous equations for other scrubber types presented in the Scrubber Handbook.[4] In turn, this indicates the predominant mechanism for capture of particles larger than about 0.5 μm in scrubbers is impaction, as postulated there. (For much smaller particles, Brownian diffusion produces effective collection.) Equations (1) and (4) and their analogues help clarify the ways in which scrubber efficiency might be increased.

It is highly desirable to increase scrubber efficiency without increasing the power consumption, a major cost component. Candidate methods for increasing scrubber efficiency are: increase impaction or other types of particle capture, remove interferences to capture, and prevent the escape of scrubber liquid which contains particulate material or soluble solids.

Particle collection by impaction would be increased by increasing the following (refer to equations (3) and (4):

- Cunningham correction
- Particle density
- Particle size
- Gas velocity
- f factor.

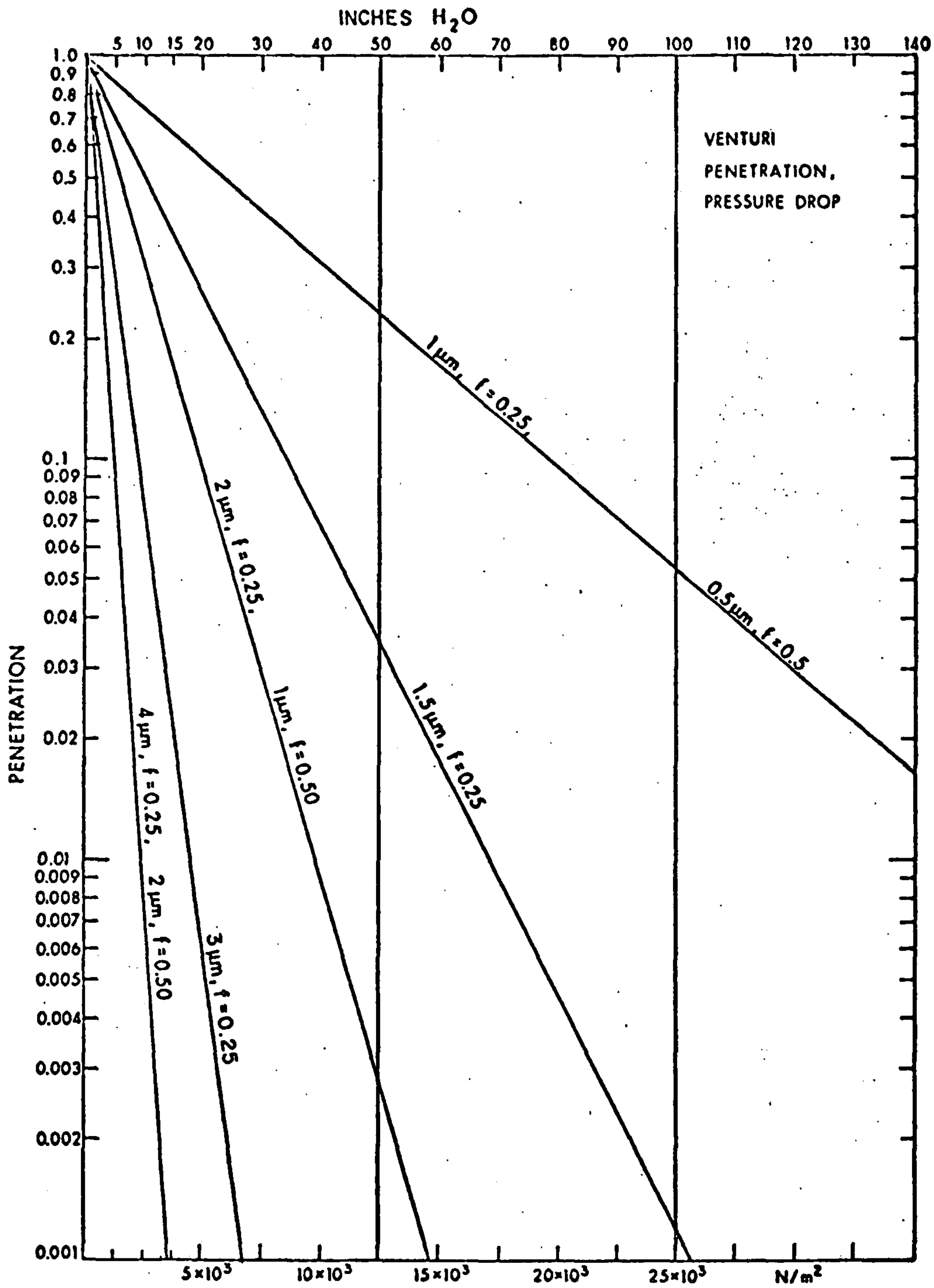


Figure 3. Penetration calculated from a venturi scrubber model as a function of pressure drop and particle aerodynamic diameter (corrected version of Scrubber Handbook[4] figure)

Unfortunately, particle density is usually inconvenient to increase. The Cunningham correction is also difficult to alter favorably, as it decreases with increasing particle size. One can increase particle size fairly easily by condensing water vapor on the particles, so this is an attractive direction to go for improvement. From Figure 3 it can be seen that dramatic changes can result from doubling the particle size. Although increasing the gas velocity will improve impaction, it is costly in power consumption, the power depending upon gas velocity linearly or even more strongly. The f factor may be amenable to change through improved wetting of particles or through improvements in flow profiles and scrubbing liquid distribution. Collection efficiency due to impaction can also be improved by decreasing the following:

- Scrubbing droplet size
- Gas viscosity.

The drawback to decreasing droplet size is that it takes more energy to produce a small spray droplet than a big one (compare their surface free energies), so that improved collection by impaction by this method has an energy penalty. Gas viscosity does decrease with decreased temperatures, so that cooling the gas can save energy and improve collection efficiency. The most promising approaches to improved collection efficiency due to impaction without major energy cost seem to be: increasing the particle size by condensation of water vapor and increasing the f factor, perhaps by improving wettability.

Having discussed the possibilities for increasing collection by impaction, we turn our attention to other methods for improving particle capture by the scrubbing liquid. The following mechanisms might be employed to enhance collection by producing larger migration velocities toward the liquid:

- Electrostatic forces
- Diffusiophoresis
- Gravitational sedimentation

- Thermophoresis
- Brownian diffusion

Electrical attraction between particle and scrubbing liquid will enhance collection; it can be shown that this should be possible with very little additional energy consumption, making this an attractive direction for research and development. Diffusiophoresis is particle motion produced by vapor gradients, the most common being the motion toward or away from a liquid surface due to condensation or evaporation. As will be seen, diffusiophoresis due to condensation can be used to improve scrubbing efficiency. Condensation also releases heat energy rather than requiring an energy input. Sedimentation can only be effective if the gravitational force has time to produce a settling distance which is comparable in dimension to the collector geometry. For particles smaller than about a micron, there is negligible gravitational settling.[6] For larger particles, the mechanism could be useful, but the residence times in the control system would still have to be relatively long, requiring large structures with high initial construction costs; thus, sedimentation is not very promising. Thermophoresis is the motion of particles in a temperature gradient due to greater transfer of momentum from the gas on the hotter side than on the cooler side of the particles; the force is relatively weak in comparison to other forces normally operant in control contexts. Diffusion occurs due to Brownian motion; it increases as particle size gets smaller and as gas temperature increases; to heat the gas to improve diffusive deposition would carry a substantial energy cost. As this discussion indicates, two promising methods of efficiency improvement would be the addition of electrostatic forces and the use of condensation to produce diffusiophoresis. (Recall that condensation also causes particle growth, thus improvement in impactive collection.)

Collection by the scrubber liquid is necessary but not sufficient. No matter how well the scrubbing liquid captures particulate material, the liquid and its entrapped particulate matter must be prevented from being passed to the atmosphere. This requires minimizing the formation of unwanted droplets and assuring the capture of droplets through the use of mist eliminators, topics of relatively little prior investigation.

In the light of this discussion, it is understandable why IERL-RTP has selected the following areas for research and development in scrubber technology:

- Enhanced impaction by increasing particle size through the use of water vapor condensation
- Increased migration velocities by addition of diffusiophoretic force through condensation
- Increased migration velocities by addition of electrostatic forces
- Higher f factor values, perhaps by improved wettability
- Reduction of droplet-borne emissions by the improvement of mist eliminators.

The logic of this course is to improve the major mechanism (impaction), as feasible; increase collection by incorporating other mechanisms (diffusiophoretic and electrostatic), where practicable; diminish any interference with collection which might be due to wettability (the f factor); and finally, prevent those particles which have been captured from escaping to the air (entrainment minimization and mist elimination). Each of these areas will be discussed in more detail in what follows.

ELECTROSTATIC AUGMENTATION

Electrostatic precipitators produce relatively high efficiency collection at relatively high capital expenditures and relatively low power costs, in comparison with scrubbers and filters of comparable particle collection efficiency. Augmenting the inertial impaction mechanism with electrical attraction was viewed by IERL-RTP as a means for improving scrubber efficiency with little additional power cost, and three major programs have been sponsored toward this goal, one each at MIT, TRW, and the University of Washington.

Equations for the various electrostatic forces which are important in particle collection have been presented by Kraemer and Johnstone and are also available in the classic work by Fuchs.[6] Basically, these forces are of two types:

- Attraction or repulsion of a charged particle due to charge on other particles or collectors (Coulomb force)
- Attraction of uncharged bodies to charged bodies (dipole force or image force)

Recently, Cooper[7] evaluated these forces for reasonable values of the relevant parameters, as part of a IERL-RTP-sponsored review of electrostatic augmentation, and found the Coulomb force to be quite clearly predominant, generally. The migration velocity, w, produced by these forces is the product of the force and the particle mobility, available from tables, such as those given by Fuchs.[6] (Particle mobility is terminal velocity per unit applied force.) The influence of such forces will become important when the migration velocities they produce are comparable to the product of the single target impaction efficiency and the relative gas/droplet velocity.

Under a contract with IERL-RTP, Melcher and Sachar[8] of MIT studied experimentally and theoretically the various combinations of charged droplets and particles which might be used in electrostatically augmented spray scrubbers. They defined characteristic times for various particle and droplet behavior, and from these characteristic times the collection efficiency of such a system could be determined. They confirmed their theoretical predictions experimentally.

Lear, Krieve, and Cohen[9] of TRW published the results of their IERL-RTP-sponsored work with a novel control device, the Charged Droplet Scrubber. The scrubber accelerates the scrubbing droplets by using electrostatic forces rather than hydraulic or aerodynamic forces. The droplets capture some of the particulate material by conventional impaction, etc., and the droplets charge other particles, those which come sufficiently close to cause an electrical discharge from the charged droplets. The droplets and the charged particles are then caught on the conductive surfaces of the scrubber due to the electric field which is set up by the high voltage nozzle and grounded surfaces.

The collection efficiencies for the laboratory-scale Charged Droplet Scrubber were higher than those for conventional scrubbers of similar power consumption. The work done to accelerate the droplets should be very much the same for this kind of scrubber and for a conventional scrubber; thus the power requirements would be much the same with the exception of pump or fan efficiency factors versus the electrostatic spray nozzle efficiency factors. The major source of improvement on conventional scrubber technology would be the addition of considerable electrostatic force, especially useful in the range 0.1 to 1 μm, where scrubbers normally have their efficiency minima.

Research at the University of Washington under the direction of Dr. Michael Pilat had shown that charging particles and spray droplets to opposite polarities can improve scrubber efficiency dramatically, especially in the submicron range. Figure 4 is from an article by Pilat.[10] It shows collection efficiency as a function of particle size for two conditions: oppositely charged particles and droplets, and electrically neutral particles and droplets. The power consumption was 0.5 hp/1000 acfm (0.8 kW/(m^3/s)), quite low for a scrubber of high efficiency (90 percent) at 1 μm. IERL-RTP is sponsoring further work on this scrubber: the development and testing of a 1000 acfm (0.47 m^3/s) model, with the testing specifically directed toward answering the questions that would be necessary for construction of a full-size device. Efficiencies, particle characteristics, and gas characteristics will be determined as part of this program.

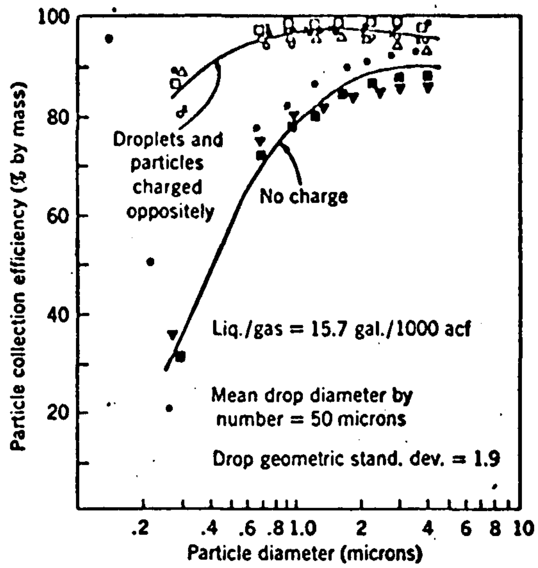


Figure 4. Particle collection efficiency of electrostatic spray droplet scrubber as a function of particle size[10]

In summary, the option of increasing scrubber efficiencies at moderate power levels by the addition of electrical forces is being pursued in a number of programs sponsored by Industrial Environmental Research Laboratory-Research Triangle Park.

FLUX FORCE/CONDENSATION (FF/C)

In particle collection by wet scrubbers, the role of condensation effects associated with the presence of vapor in the gas stream is presently the subject of intensive investigation. The idea of using these effects, however, is not new, dating from the turn of the century. These effects augment the usual mechanisms of Brownian diffusion and inertial impaction. When vapor condenses onto a scrubber droplet, a diffusiophoretic force is exerted on particles in the direction toward the droplet surface. This force has two sources: the net flow of water molecules to the droplet, a "wind" of sorts called "Stephan flow," and a subtle component due to the gradient of the water vapor and the difference between its molecular weight and the molecular weight of air. When vapor condenses onto the particles, the particles become effectively larger and are therefore more easily captured by settling or by inertial impaction. These effects seem to be important for submicron particles. Still uncertain is the importance of the thermophoretic force, associated with heat flow and in the same direction as the heat flow: the particles are driven toward the drop surface when the drop is colder than the gas. The terminology "flux force" applies here to the forces of diffusiophoresis and thermophoresis. As opposed to conventional scrubbers, FF/C scrubbers often require the introduction of steam, which increases their expense of operation if the steam is to be purchased.

Available theoretical and experimental evidence is apparently not yet conclusive regarding degree of improvement of collection efficiency by condensation effects. Sparks and Pilat[11] performed calculations of particle collection efficiency by droplets under conditions assuming that (1) condensation, or (2) evaporation, or (3) neither, is occurring. The mechanisms were assumed to be inertial impaction and diffusiophoresis. Simultaneous condensation was shown to enhance, while simultaneous evaporation was shown to diminish, the collection by inertial impaction, the enhancement - diminution effect being more pronounced for the smaller particles. (Thermophoresis was assumed to be negligible). Lancaster and Strauss[12] concluded that diffusiophoresis is not significant in conventional scrubbers in which steam is injected. On the other hand, Fuchs and Kirsch[13] showed that high condensation rates lead to significant improvement. IERL-RTP-sponsored studies by APT, Inc.[14] and Stanford Research Institute[15] showed that diffusiophoresis is significant in FF/C scrubbers and in conventional scrubbers with steam added. Collection is also enhanced by additional stages, whereby particle enlargement can contribute. (A list of major references is available in a report by APT, Inc.[14])

In 1951, Shauer[16] conducted experiments in which the flue gas from the combustion of radioactive wastes was drawn into a steam exhauster and the resulting aerosol-steam mixture was expanded through a nozzle, causing condensation of the aerosol particles. The nozzle system was followed by a spray scrubber. Efficiencies up to 99.9 percent were obtained for 0.3 μm DOP (di-octyl phthalate) particles, as opposed to zero efficiency without steam addition. (Energy consumption was great, however.) Schauer attributed the improvement to particle enlargement by condensation.

The diffusiophoresis "flux force" mechanism is discussed in detail by Waldmann and Schmitt.[17] The existence of this mechanism is evident from the experimental results of Lapple and Kamack (1955)[18] and Semrau et al. (1958).[19] Semrau et al., for example, noted a large difference in efficiency between wet scrubbers operating with hot and cold water sprays. They suggested the differences could be caused by evaporation from the hot water droplets, which would produce a diffusiophoretic force away from the drop surface and therefore would result in reduced efficiency. (This would correspond to "evaporation scrubbing" as opposed to "condensation scrubbing").

The possible dominance of thermophoresis over diffusiophoresis under some conditions is proposed by Slinn and Hales[20] in contradiction to others such as Goldsmith and May[21] who argue that thermophoretic forces should be negligible. Two kinds of experimental results seem to support the latter: improved scrubbing under condensing conditions and the formation of a "dust-free" space observable near the surface of an evaporating droplet.

In studies supported by IERL-RTP (Calvert et al.[14] and Calvert and Thaveri[22]), APT, Inc. showed that FF/C scrubber efficiency is insensitive to particle size. Therefore FF/C scrubbing is potentially competitive with high-energy scrubbers when high collection efficiencies for fine (submicron) particles are required. In the APT, Inc. studies it was also found that FF/C collection increases as the concentration of particles decreases. This can be understood on the basis that the available moisture is shared by fewer particles, which thereby grow larger and are collected more easily than otherwise. Thermophoresis was shown to be of minor importance compared with diffusiophoresis and the effect of particle enlargement by condensation.

Other studies (multiple plates, etc.) have been sponsored by IERL-RTP, including those of APT, Inc.[14] and of Stanford Research Institute.[15] In a study by APT, Inc. on FF/C (flux-force/condensation) scrubbing, Calvert et al.[14] showed that collection increases with the quantity of water vapor condensed per unit quantity of gas, and that diffusiophoresis was the major collection mechanism for a single-sieve-plate scrubber. In a subsequent study of multi-stage collection, Calvert and Jhaveri[22] found collection was much greater than on single-stage devices; this is presumably due mainly to effects whereby particles enlarged by condensation can be collected by downstream stages. Effects of water vapor condensation and evaporation in conventional scrubbers (cocurrent-contact orifice type) were studied by Semrau and Witham.[15] At a given pressure drop, condensation of substantial amounts of water was found to increase the collection, whereas the opposite effect was achieved by vaporization. This implies that diffusiophoresis is significant. Particle growth effects were minor in this single-stage scrubber.

ENTRAINMENT SEPARATOR TECHNOLOGY

All particulate control scrubbing involves the energetic interaction of the gas stream and the scrubbing liquid, usually water. Often this means that entrained water droplets containing contaminants will exit from the scrubber unless some means of demisting, or entrainment separation, is employed. The dried residue from these water droplets form an air pollution source. (In the novel control device evaluation program of IERL-RTP there have occasionally been observed net <u>increases</u> in particulate matter in certain particle size ranges, thought to be due to evaporation of scrubbing liquid containing dissolved solids, such as hard water.)

Increased emphasis on entrainment separation has accompanied the development of scrubbers which remove SO_2 with drops containing limestone or other reactants. Emission of these droplets to the atmosphere would produce substantial quantities of particulate pollution, for example in the use of limestone scrubbing to remove SO_2 from flue gases. Nannen et al.[23] indicated that for a packed tower scrubber there would be a liquid-to-gas ratio of about 50 gal/1000 ft^3 or 6.7×10^{-3} m^3/m^3 and the liquid would be about 10 percent solids by weight. Thus the ratio of scrubbing solids to air volume would be would be about 670 g/m^3 or 290 gr/ft^3, and the escape of only 10^{-3} of this solid material as part of droplets would produce heavy emissions. It is desirable both to minimize reentrainment and to use mist eliminators to capture the liquid which is entrained. Demisters are effective for drop sizes above a few microns in diameter. Their effectiveness may be assessed in terms of three criteria:

- Primary collection efficiency (should be high)
- Pressure drop (should be low)
- Reentrainment rate (should be very low)

Primary collection of mist exceeds total collection by the amount of the reentrainment, which normally does not occur at low gas velocities. There is a critical value of gas velocity at which reentrainment occurs, and above which the total collection efficiency is thereby reduced.

Until recent work by APT, Inc. under IERL-RTP support,[24] little was known about entrainment separator technology, in particular the reentrainment rate. In the scrubber industry 100 percent overall efficiency has been generally assumed for entrainment separators.

The APT, Inc. work included theory for primary collection efficiency, pressure drop, and reentrainment in baffles and cyclones. This work also included pilot-plant experiments with various types of separators. The theoretical models generally agreed with experimental data, except that the reentrainment theory was found to underestimate the observed reentrainment. Above the critical velocities, reentrainment values about 0.5 to 1.0 percent were observed, and the minimum drop size in the reentrainment was 40 μm, although Statnick and Drehmel,[25] among others, have reported capturing droplets on cascade impactor stages with size cut-offs on the order of micrometers, which may be due to entrainment or, more likely, to condensation. The entrainment separator is now considered an important part of any scrubber system, representing significant capital and operating costs. Contributing to these costs is the fact that the entrainment separators must be operated at low velocities, leading to large sizes and therefore large costs.

Such work is to be carried further by APT, Inc., under sponsorship by IERL-RTP, in ascertaining the characteristics of the entrainment from a mobile bed scrubber (TCA), similar to those found to be unusually energy-efficient in producing high efficiency control of fine particulates. Thus, two important areas of Industrial Environmental Research Laboratory-Research Triangle Park research are merged.

EFFECTS OF INTERFACIAL PROPERTIES ON SCRUBBING

Up to this point we have discussed mechanisms such as impaction, electrostatic migration, and diffusiophoresis for bringing particles into contact with the scrubbing liquid. Contact and capture are not synonymous, however. Particles may rebound from the surface, and difficulties observed in some scrubber applications have been ascribed to the nonwettability of the particles by the droplets. The importance of surface properties in scrubbing is a matter of scientific debate, some of which we will present here, but IERL-RTP hopes to provide definitive answers through its recent sponsorship of a new investigation of these effects.

Wetting, a seemingly simple process, is actually a subtle physicochemical interaction. According to Berg et al.[26] the wetting of solids by water consists of the formation of hydrogen bonds between H_2O molecules in the droplets and OH on the surface of the solid. The rate at which the process proceeds can be critical, and it depends upon many factors. The removal of particulate material from gases by moving drops has been of considerable interest in the contexts of scrubbing and of the precipitation scavenging from the atmosphere of radioactive debris, in which context Engelmann described the effects of wettability on particle raindrop collisions.[27] Nonretention of particles can be due to (a) rebound from the drop surface, (b) rebound from another particle already on the surface, or (c) reentrainment by the drag of the air. There are two somewhat different cases: liquid-solid and liquid-liquid contact.

Coalescence of water drops with one another has been studied for almost a century, beginning with the work of Rayleigh.[28] However, it has been apparently much more difficult to obtain reliable experimental data on the retention of solid particles (dust, for example) by water drops. In recent experimental work reported by Fuchs et al.,[29] dust particles (quartz, carborundum, and coal) 5 μm to 80 μm in diameter were observed to be almost entirely retained upon contact with a water drop 1 to 2 mm in diameter, at relative velocities of 1 to 6 m/s. However, these results must be considered tentative; there is room for doubt regarding the high degree of retention because it was not certain that all particle rebounds were observable, particularly at the smaller particle sizes.

It was also observed by Fuchs et al.[29] that the captured particles remain on the surface when the drop is pure water, but penetrate into the interior when the drop is an aqueous solution of surfactant. The effects of wetting seemed to become important only at small relative impact velocities.[6] Wettability of a particle is sometimes assumed to be the same as the wettability of the solid bulk material, which is defined in terms of the equilibrium contact angle between a water drop and a plane surface of the material. The interaction between a particle and a drop depends on the dynamic rather than the static surface tension because the liquid surface undergoes rapid extension during the collision, according to Fuchs.[6]

There are other difficulties, such as the fact that minute amount of impurities radically change the surface properties. The adhesion between a drop and a solid surface is different for a dry surface and for a surface which has previously been wetted, even for a very short time;[30] a layer of grease only one molecule thick can increase the contact angle significantly.

In Rayleigh's experiments in 1879,[28] colliding water drops were observed to bounce apart in the absence of electric charge; that is, charge was found by him to be essential for coalescence between water drops. This was confirmed by Berg,[31] who found that the time required for coalescence of water drops, and for the wetting of solid particles, depends on electrical potentials.

In later work, Berg et al.[26] showed that:

1. Wetting is a rate process; if the rate is not large enough, colliding solid particles and water drops bounce apart.

2. A solid salt that is hydrated such as to have a saturated solution at the surface is wetted at the same rate as that of two colliding water drops; this rate is determined by the rate at which hydrogen bonds are reoriented across the interface, and this requires an orienting electric field, that is, charged colliding partners.

3. A solid covered with OH is more rapidly wetted than one covered with H_2O; this is because reorientation of bonds is required on the part of both partners in the latter case, as opposed to the water drop alone in the former case (electric charge required).

In theoretical treatments to date (McCully et al.,[32] Pemberton,[33] McDonald[34]), wetting is assumed to be associated with the mechanical problem of the deceleration of the impacting particle by the drop surface tension. Pemberton[33] equated the particle kinetic energy to the work necessary to overcome surface tension and penetrate to the drop interior. He found a minimum velocity u for penetration for a completely unwettable particle:

$$u = \left(\frac{8\tau}{\rho d_p} \right)^{1/2}$$

where τ is surface tension, and ρ and d_p are the particle density and diameter, respectively. McDonald[34] extended this theory to arbitrary contact angles (equilibrium or static), and considered the conditions under which the particle would "shoot through" the drop. These theories do not consider the dynamic surface tension as suggested by Fuchs.[6]

Fuchs et al.[29] concluded from their observation of captured unwetted particles remaining on the surface that Pemberton's concept is unrealistic: namely, in order to be captured, particles must be completely engulfed by the drop. On the other hand, the work of Berg et al.[26] shows that charge is probably present, and this would explain the observations of Fuchs et al.[29] as well as those of McCully et al.[32] that unwetted particles remain on the surface.

Because of the remaining questions related to wettability, etc., IERL-RTP has initiated a program for determining interfacial property effects on scrubbing.

SUMMARY

Scrubber technology seems to have reached the practical limits of performance for the use of inertial impaction. (Possible exceptions may be represented by the mobile bed scrubber, TCA, and low energy scrubbers used in series.) Attention has turned to improving scrubber performance by introducing new forces (electrostatic, diffusiophoretic) or by increasing impaction and interception by using condensation to increase the physical size of the particles being scrubbed. Removing the entrained water from scrubber exhaust is needed to achieve maximum benefits from the control system. In some cases, nonwettability of the particulate matter may cause a scrubber system to work much less effectively than predicted. All of these subjects are being covered or have been covered by the Industrial Environmental Research Laboratory-Research Triangle Park scrubber program.

More detail on the specific projects in the IERL-RTP scrubber program are provided in the next section, which presents a chronological overview of the program.

SECTION V

CHRONOLOGICAL OVERVIEW

This section describes the projects sponsored by Industrial Environmental Research Laboratory-Research Triangle Park in chronological order, by starting date. Where our information was sufficient, we have followed our introductory remarks for each study with material describing its goals, methods, results, conclusions and recommendations.

WET SCRUBBER SYSTEMS STUDY (APT, INC., 1970)

Introduction

IERL-RTP contracted with Ambient Purification Technology, Inc. (now APT, Inc.) to perform a study and review of scrubber technology. The study was to yield a thoroughly documented engineering handbook (Scrubber Handbook)[4] suitable for scrubber design, which would also aid future development by setting forth the state of the art.

Goals

As presented in the Scrubber Handbook,[4] the goals of the APT, Inc. study were:

1. Evaluate current engineering technology
2. Evaluate existing scrubber systems
3. Investigate present usage problems
4. Determine potential new applications
5. Develop specific research recommendations

Methods

The study involved analysis, but not new experimental work. The products of the review were: (1) the Scrubber Handbook, (2) Final Report, (3) Bibliography, and (4) Research and Development Plan. The handbook involved both selection from the literature and development of design criteria and theoretical and empirical relationships for wet scrubbers intended to cleanse both particulates and gases from the effluents of stationary sources, with emphasis on particulate scrubbing. Much information on scrubbers was gathered by questionnaires submitted to scrubber manufacturers and actual on-site observation of scrubber operations. Compilation of the bibliography was assisted by computer search. The Scrubber Handbook treated scrubbers by analyzing "unit mechanisms" for collection of particulates and gases, a significant contribution to analysis. Particular scrubbers were then analyzed as being dependent upon a group of unit mechanisms for collection. For collection of particles, the unit mechanisms considered were: inertial collection, interception, diffusion, electrostatic migration, diffusiophoresis, thermophoresis, and condensation. A method was developed for calculating the penetration for a polydisperse aerosol conveniently. For gases the unit mechanisms were: transfer to drops, transfer to liquid films, and transfer within bubbles.

Results

The results of the study are summarized by a portion of the abstract to the Scrubber Handbook: "The Scrubber Handbook brings together previously scattered material and makes clear its applicability to scrubber technology. It discusses the various aspects of scrubber use and presents engineering design methods based on a unifying concept. Actual experience on hundreds of scrubber installations is presented in a condensed form. Many related topics such as auxiliaries, cost estimation and optimization techniques, and the disposal of liquid and solid wastes are all covered ....." The bibliography contains about 1,700 references discussing various aspects of wet scrubbers.

The subject areas and organization of the Scrubber Handbook are:

Chapter 1 - Introduction
Chapter 2 - Guide to the Handbook
Chapter 3 - Scrubbers Available
Chapter 4 - Basic Concepts
Chapter 5 - Design Methods
Chapter 6 - Auxiliaries
Chapter 7 - Scrubber Performance on Industrial Emissions
Chapter 8 - System Analysis, Costs, and Optimization
Chapter 9 - Design Examples
Chapter 10 - Physical and Chemical Data
Chapter 11 - Materials Data
Chapter 12 - Liquid and Solid Waste Disposal

Conclusions and Recommendations

The Final Report of the study presents two R & D plans; one at a $2 million, 5-year level, and the second at a $7 million, 5-year level.

The major objectives of the R&D effort proposal were:

1. Basic Concepts Research - Experimental verification of particle collection mechanisms theory; study of mechanisms of agglomeration; experimental study of mass transfer coefficients in two-phase flow; experimental and theoretical study of interfacial areas.

2. Physico-Chemical Data - Study of reacting solutions and slurries to determine reliable gas- and liquid-phase diffusivities for SO_2 and other pollutants.

3. Design of New Equipment - Utilization of additional forces and agglomeration; use of smaller scrubbers and higher gas velocities; alteration of liquid properties to increase collection efficiency.

4. Engineering Design and Optimization of Scrubber Systems - Development of standard methods for evaluating wet scrubbers; formulation of collection efficiency equations for multiple collection mechanisms; development of calculation method for converting collection efficiency data from hygroscopic to nonhygroscopic particles; optimization of scrubber systems.

5. Dynamic Behavior and Control Instrumentation Technique - Theoretical and experimental study of scrubber system response to start up, shut down, and overload surges.

FEASIBILITY OF FLUX FORCE/CONCENTRATION SCRUBBING FOR FINE PARTICULATE COLLECTION (APT, INC.)

Introduction

This work represents a follow-up to the preceding scrubber study by APT. In the previous work it was learned that, in fine particle collection by liquid drops, collection by the usual well-known mechanisms (such as Brownian diffusion and inertial impaction) is aided by additional less well-known mechanisms, "flux-force" and condensation effects. The term "flux-force" is defined to include thermophoresis, diffusiophoresis (and Stefan flow), and photophoresis, all of which result in body forces acting on particles; of interest are conditions under which these forces drive the particles toward the collector drop surface. One condensation effect is to cause particles to become enlarged, by the accretion of liquid due to vapor condensation; the enlarged particles are subsequently more easily collected by impaction and interception.

The phenomena of flux forces and of condensation enlargement had been observed earlier, as discussed in Section IV herein. Simple theories were available to describe them individually in simple cases. There did not exist, however, a quantitative model which (1) describes the simultaneous action of phoretic forces and condensation enlargement (the combination denoted by the symbol FF/C), and (2) predicts particle collection efficiency in practical scrubber systems incorporating FF/C. Hence, the study was undertaken to determine the feasibility of FF/C scrubbing. Its scope was restricted to the specific phenomena of diffusiophoresis, thermophoresis, and particle enlargement by condensation.

Goals

The purpose of the study was to determine whether FF/C effects are sufficiently important to warrant further development, and, if so, to recommend a program of further research. The main tasks included:[14]

1. Review of existing theory on FF/C effects (see Scrubber Handbook, for example) and extension thereof toward developing engineering design methods suitable for evaluation of practical scrubber systems.

2. An experimental study to explore and evaluate the important features of FF/C scrubbing.

3. Preliminary engineering and cost analyses of promising practical cases.

4. Recommendations for future FF/C scrubber system development.

Methods

A literature review was carried out to obtain available background information on FF/C scrubbing. Engineering design involved analyses of several factors: particle growth; energy balance, including latent heat (to determine the temperature) for the liquid interface; the rate of vapor condensation (on particles and on collector surface); and particle deposition rates. Based on available theories for deposition velocities and for particle enlargment by condensation, mathematical models (i.e., design equations) were developed for spray, sieve-plate, impinging-jet, and liquid-sheet (wetted-wall or packed bed) scrubbers.

Theory - In the APT, Inc. study a mathematical model was developed for sieve plate scrubbers as well as for other types of scrubbers, and experiments were performed on a sieve plate scrubber. The sieve plate scrubber is an alternative to scrubbers that use droplets. A bubble layer on a plate represents a large collecting surface area. The principal mechanism for gas/liquid contacting involves bubble formation and rise through the liquid. The mathematical model involves:

1. Heat and mass transfer between bubbles and liquid.
2. Heat and mass transfer between bubbles and particles suspended in the bubbles.
3. Particle growth due to condensation.
4. Particle deposition by (a) diffusiophoresis, (b) thermophoresis, (c) centrifugation during bubble rise.

The temperature of the liquid interface depends on the gas/liquid heat and mass transfer coefficients, the liquid-phase heat transfer coefficient, the nature of the interfacial area, and the flow patterns of the two major phases. Simple models may be inaccurate because they do not account for the manner in which local gas velocity and overall gas flow patterns influence both local transfer coefficients and bulk conditions for the phases in contact in any region. The latter are also influenced by the liquid-phase hydrodynamics, which is very complicated in bubbling systems. In plate-type scrubbers, particles are collected during bubble formation, and this becomes important after particle growth takes place. This effect is a function of foam density, as well as particle properties, plate geometry, and gas velocity. When vapor is condensing, the foam characteristics are changed from normal (noncondensing) conditions.

Experiment - Based on theory, APT decided to verify assumed transfer coefficients in an experiment using a sieve-plate scrubber. The particular transfer coefficients needed for predicting penetration under given experimental conditions are the gas-phase and liquid-phase heat transfer coefficients, and the gas-phase mass transfer coefficient.

The major components of the experimental apparatus consisted of:

1. A test section with an aluminum sieve plate, of diameter 10.2 cm and thickness 1.6 mm, having 30 perforations 4.8 mm in diameter adding up to 6.6 percent free area.

2. An air flow system, controlling air flow rate (up to 0.71 m^3/min and temperature), water vapor, and aerosol particle concentration (up to $10^6/cm^3$).

3. A particle generator, using a Collison atomizer with dibutyl-phthalate (DBP), an impactor, and an evaporation-condensation generator. (Particle diameters were in the range 0.5 μm to 1.0 μm.)

4. A particulate sampling system, using filters, a Climet photocounter, and an eight-stage Andersen cascade impactor.

The object of the experiments was to infer values of the transfer coefficients required by the mathematical model.

In the experiments, the liquid-to-gas-flow-rate ratio (L/G) was kept high (average value = 7.7 ℓ/m^3) in order to maintain a low liquid temperature on the sieve plate, and therefore, a high diffusiophoretic force due to vapor condensation of the bubble wall. The collection was attributed to the combined effects of:

1. Impaction during bubble formation
2. Diffusiophoresis
3. Thermophoresis
4. Diffusion
5. Particle condensation-enlargement with centrifugal force

The diffusiophoretic collection was found to depend on the amount of vapor condensed per unit volume of gas, and the collection is higher for higher water vapor concentrations, at a fixed temperature.

Comparisons were made between the predicted and the measured values for heat and mass transfer coefficients. The predicted value of the liquid-phase heat transfer coefficient was of the order of 100 times larger than the empirically determined value. This casts doubt on the assumptions regarding the bubble area available for transfer, the bubble diameter, the liquid temperature, the liquid surface renewal time, and the uniformity of the foam density.

Results

One result of the work was the finding that diffusiophoresis was the major collection mechanism for a single plate scrubber. Diffusiophoresis depends on the amount of vapor condensed, which can be expressed as the parameter $(y_i - y_e)$, or moles of vapor condensed per mole of dry air. Figure 5 shows experimental penetration, $\overline{Pt}$, as a function of this parameter. (The six data points are labeled by the run numbers.) The variation of $\overline{Pt}$ is due to the diffusiophoresis, while the contributions of the other mechanisms (impaction during bubble formation, thermophoresis, diffusion, and condensation growth) are approximately the same for all the runs. In the figure, Pt_F refers to impaction during bubble formation. Particle enlargement by condensation was an unimportant effect, probably because the DBP particles were not very wettable. Another reason is that this was a single stage device. Subsequent work has shown this enlargement to be significant for multi-stage devices: particles "grown" in the first stage are more easily caught in later stages. It was found that the theoretical model satisfactorily predicts the general form and magnitude of the experimental results if particular values are used for the heat and mass transfer coefficients. Theoretical values of the transfer coefficients obtained using penetration theory were found to agree with the corresponding experimental values for the gas-phase heat and mass transfer, but not for the liquid-phase heat transfer, as noted above. It was thereby inferred that there may be

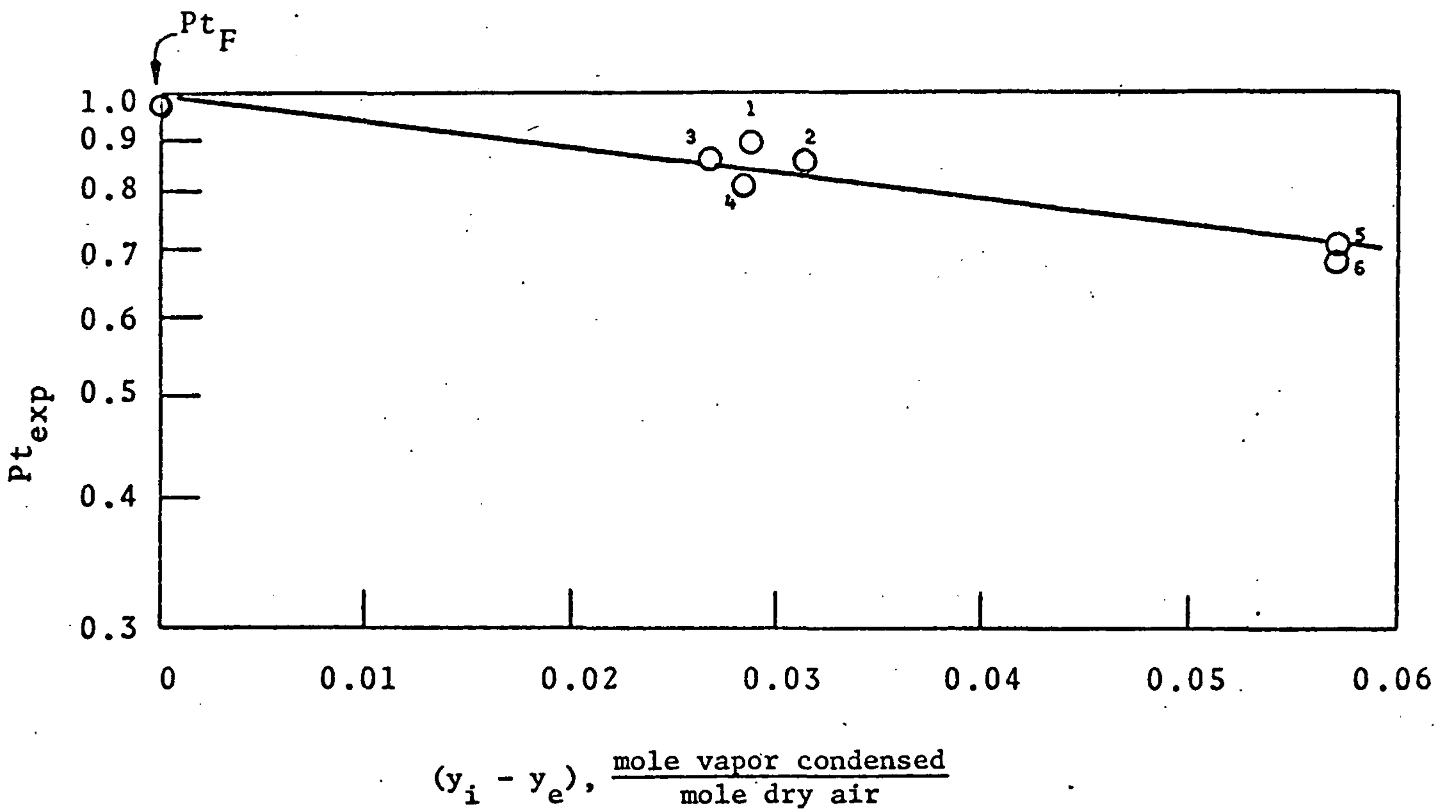


Figure 5. Particle penetration versus water vapor condensed

errors in the assumptions regarding the bubble area available for transfer, the bubble diameter, the liquid temperature, the liquid surface renewal time, and/or the consistency of the foam density. These results were felt to indicate a need for further experimental and analytical work. Moreover, the predicted particle collection values were found to be higher than the experimental inferred values.

Conclusions

Calvert, et al. reached the following conclusions:[14]

"Overall, the comparison of experimental data with predictions based on our mathematical model shows that the model is capable of giving useful and realistic results. While additional refinement... is needed, the model can account for what is observed experimentally and gives us a good tool for interpreting what we see and utilizing this knowledge for engineering design of practical equipment ....

"The primary objective of investigating the feasibility of FF/C scrubbing has been achieved with a clearly affirmative result. It has been shown in the present program that FF/C scrubbing can remove fine particles at high efficiency and that, within some limitations, it is more economical than other means of particle collection. Mathematical modeling of the many simultaneous phenomena taking place in an FF/C scrubber has been accomplished for some important unit mechanisms, although several coefficients remain to be fitted to experimental data.

"In accordance with the original objective of selecting and performing a brief exploratory experiment of significant nature, our experimental work extended over a narrow range of conditions. Within this range the agreement between theoretical predictions and experimental results for particle collection is fairly good, once the heat and mass transfer coefficients are evaluated from experimental data. However, despite the good agreement, theoretical predictions of collection efficiency for plates are consistently higher than the experimental results. This, along with the discrepancy between computed and predicted liquid-phase heat transfer coefficients, indicates that the mathematical model for bubbles should be revised."

Recommendations

To achieve the objective of building a working FF/C scrubber, Calvert, et al. suggested further developmental investigations.

They recommended completing the experimental evaluations and development of the theoretical models for bubbles, sheets, and drops. In follow-on work, they proposed that attention should be given to:

1. Better estimates of heat and mass transfer areas
2. Better estimates of liquid surface temperature
3. Possibly unusual sieve plate design and operating conditions
4. Different bubble shapes and gas dynamics, causing different transfer rates and particle deposition by centrifugal force
5. Measurement problems that may cause errors.

New experiments for testing assumptions in the theory of bubbles and sheets should provide:

1. Test particles having a range of surface properties, and high vapor pressures to minimize vaporization up to 80°C gas temperatures.
2. Wettable particles to study the effects of growth, at relatively low saturations
3. Large gradients in water vapor concentrations simultaneously with low saturation (high gas and liquid temperatures, with nonwettable particles) to avoid condensation on the particles

4. Sieve plates with customary dimensions for mass transfer, at usual gas velocities

5. Packed columns to validate the "liquid sheets" model (to provide a more definable transfer surface area and liquid renewal time).

Calvert, et al. also suggested defining and developing an optimal FF/C scrubber, and field testing a pilot-scale FF/C scrubber.

WET SCRUBBER DEVELOPMENT II (FLUX FORCE/CONDENSATION (FF/C) SCRUBBERS) (APT, INC., 1973-1975)

This study brings the FF/C scrubber to the pilot plant development stage after earlier theoretical and experimental analysis (also under IERL-RTP contract) showed the feasibility of flux-force/condensation mechanisms in controlling fine particle emissions. The task established for APT, Inc. by the IERL-RTP project description was

> "APT will design and fabricate two pilot scale FF/C scrubbers large enough for the exploration of scale-up problems. These devices will be used in a lab pilot experimental program to determine applicability to fine particles, develop design equations, determine optimum conditions, investigate potential operational and maintenance problems, and determine the sensitivity to particle size. Based on data collected, APT will prepare a revised engineering and cost analysis, and will submit a detailed industrial pilot test program."

The methods used by APT, Inc. were similar to their earlier work. Pilot plant studies confirmed the feasibility of FF/C scrubbing and showed that the FF/C effect on multi-stage collectors was much greater than on single-stage devices.

Results

Comparisons were made between FF/C scrubbing data obtained in the APT investigation under various conditions and scrubbing data of Rozen and

Kostin[35] for particles of 1 μm aerodynamic diameter. Figure 6 and Table 4, taken from a draft final report submitted by APT, Inc. to IERL-RTP, portrays these comparisons. Figure 6 shows particle penetration versus condensation ratio (or injection ratio) q', defined as mass of water vapor condensed per mass of dry air. As Table 4 shows, the various curves in Figure 6 compare the effects of:

- Four sieve plates versus five sieve plates,
- 0.3 μm versus 0.5 μm particles,
- Titanium oxide versus black iron oxide particles,
- Initial concentration, n_i, in the range 3×10^5 to $7 \times 10^9/cm^3$.

The data of Rozen and Kostin,[35] for 0.3 μm oil particles in alternate hot and cold sieve plates, and $n_i = 10^5 - 10^8/cm^3$, are included for comparison.

Conclusions

The following conclusions may be drawn:

- It is apparent from Figure 6 that collection increases in all cases with increasing q'.

- Five plates are significantly more effective than four (probably due mainly to particle enlargement effects).

- Scrubber performance is insensitive to the L/G ratio. (However, a lower L/G ratio with recirculated liquid requires a larger cooling range in the liquid cooling system.)

- Scrubber performance is improved significantly when the vapor condensation is distributed over two sections of the multiple-plate scrubber. This is also consistent with results of Rozen and Kostin.[35]

- Collection decreases with increasing inlet concentration, n_i. (This shows the importance of condensation enlargement, and of competition for the available vapor.)

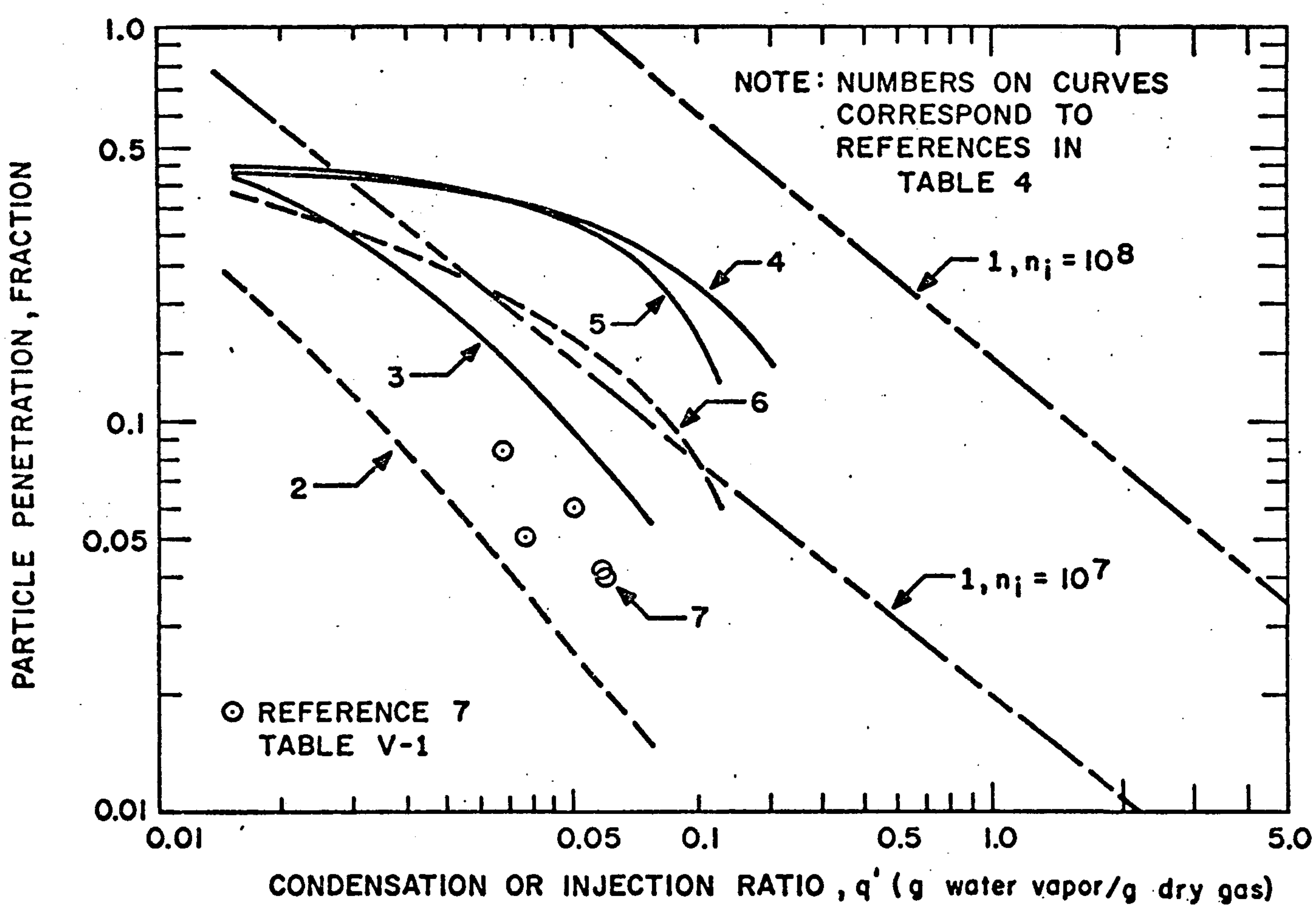


Figure 6. FF/C scrubber performance comparison (APT, Inc.)

Table 4. FF/C SCRUBBER PERFORMANCE COMPARISON

Figure ref.	Experimental studies	Scrubber type	d_{pg}[a] (μm)	Particle material	n_i[b] (cm^{-3})
1	Rozen and Kostin[35]	Alternate hot and cold sieve plates	0.3	Oil	10^5 - 10^8
2	Present investigation[c]	Five sieve plates L = 0.64 ℓ/sec	0.55	Black Iron Oxide	3×10^5
3	Present investigation[c]	Four sieve plates L = 0.64 ℓ/sec	0.55	Black Iron Oxide	3.6×10^5
4	Present investigation[c]	Four sieve plates L = 0.64 ℓ/sec	0.5	Titanium Dioxide	3×10^6 -7.2×10^9
5	Present investigation[c]	Four sieve plates L = 0.38 ℓ/sec	0.5	Titanium Dioxide	2.4×10^7 -8.8×10^8
6	Present investigation[c]	Five sieve plates L - 0.38 ℓ/sec	0.5	Titanium Dioxide	5×10^5 -1.7×10^7
7	Present investigation[c]	Five sieve plates L = 0.38 ℓ/sec Steam introduction distributed under two plates	0.5	Titanium Dioxide	3×10^5 -3.4×10^6

[a]Particle mass median diameter.

[b]Initial particle number concentration.

[c]APT, Inc. "Wet Scrubber Development II."

FINE PARTICLE SCRUBBER PERFORMANCE TESTS (APT, INC. 1974)[36]

Introduction

Testing of the fine particle collection efficiency of actual scrubber installations was undertaken by APT under contract with IERL-RTP. The program was designed to fulfill the need for more reliable data on collection efficiency than previously available, in order to design better scrubbers and to predict their performance. Inadequate methodology, undefined parameters, and insufficient quantity were cited by APT as being responsible for the shortcomings of previous scrubber testing, failings which their study attempted to rectify.

Goals

As presented in the Final Report,[36] the major objectives of the study were:

1. Obtain data on fine particle (< 2 to 3 μm) collection efficiency as a function of particle size for scrubbers operating on representative industrial emission sources. Record pertinent data on scrubber design and operating conditions.

2. Reconcile the performance data with existing mathematical models, such as those presented in the Scrubber Handbook by Calvert, et al.[4]. Where necessary and possible, develop better models and/or design approaches.

3. Obtain data on scrubber system costs for investment, operating, and maintenance.

4. Compile available information on scrubber operating characteristics and problems (e.g., entrainment), maintenance requirements, corrosion and erosion experience, and similar operational problems.

Methods

The experimental procedures employed for measuring performance were:

1. Determine gas velocity distribution at scrubber inlet and outlet by pitot tube multi-point traverse

2. Measure inlet and outlet temperatures with a thermocouple or dial thermometer

3. Measure pressure at inlet and outlet with manometer and static pressure tube

4. Obtain wet- and dry-bulb temperature measurements on sample withdrawn from stack to measure humidity

5. Measure dry gas density with pycnometer

6. Measure liquid entrainment by measuring liquid collected in precutter upstream of cascade impactor. Alternate measurement technique: dye-treated paper for drop size determination.

7. Determine size of submicron particles with diffusion battery, occasionally for particles as small as 0.01 μm.

For particle sampling and size analysis, three types of cascade impactors were used:

1. Andersen "viable" sampler (500 $cm^3/5s$) for sizing samples withdrawn from the stack, calibrated by polystyrene latex particles and a Climet particle counter. Glass fiber filter used after the impactor.

2. Brink cascade impactor (100 cm^3/s) sampling both in- and ex-stack. Same calibration as above. Glass fiber filter used after last stage.

3. University of Washington (Pilat) Mark III Cascade Impactor (500 cm^3/s) for in-stack sampling. Manufacturer's calibration used. Glass fiber filter placed after last stage.

Isokinetic sampling was employed throughout the test program. A round jet impactor having a cut diameter larger than 5 μm was used as a precutter to remove large particles from inlet samples and to remove entrained liquid from outlet samples. The parameter used to define the scrubber performance was the particle aerodynamic diameter for which collection efficiency is 50 percent, the "cut diameter."

Results

The scrubbers tested and the experimentally measured cut diameters for 50 percent penetration were:

Scrubber type	Approximate aerodynamic cut diameter, μm
Valve tray	1.2
Vaned centrifugal	1.2
Impingement plate	1.0
Wetted fiber	0.8
Venturi	0.7
Mobile bed (TCA)	0.4
Venturi rod	0.3

Extensive graphical and tabular material is presented in the Final Report[36] to indicate the raw and partially reduced data used to arrive at these results.

Conclusions

1. Arrangement of scrubber tests requires judgment in deciding on the best compromises which will yield valid data.

2. Uncertainty in penetration determinations were $\geq \pm$ 10 percent at a given diameter.

3. Comparison of experimental results with mathematical models was successful in all cases but the mobile bed scrubber (TCA). Theoretical relationship between pressure drop (or power consumption per unit flow rate) and cut diameter showed good correlation with test data, except for the TCA.

4. Experimental methods need to be streamlined for better accuracy and convenience.

5. Data on capital investment, operating costs, and maintenance generally were not available or in reliable form.

Recommendations

Additional scrubber tests were recommended for:

1. Mobile bed scrubbers on variety of sources

2. Preformed spray scrubbers

3. Venturi scrubbers at high pressure drop, with nonwettable particles and on large gas flows

4. Plate-type scrubbers on systems without condensation effects and with nonwettable particles

5. Impingement and entrainment scrubbers

6. Wet fan scrubbers

Improved experimental methods were deemed necessary:

1. Better impactor catch weighing

2. More convenient and reliable diffusion battery

3. Real-time particle size and concentration analysis

4. Aerosol dilution system (for particle counters and diffusion batteries)

5. Particle density measurement

6. Opacity measurement for saturated gas stream

Model development should be furthered with respect to:

1. Mobile bed

2. Particle growth prediction for soluble materials in near-saturated gas

3. Effect of adsorbed gases on particle growth

ENTRAINMENT SEPARATORS FOR SCRUBBERS (APT, INC., SEPTEMBER 1972)

Introduction

Scrubbers of gases and particulates usually produce entrained water droplets that have to be removed by entrainment separators if the net emissions to the atmosphere are to be minimized. Spray-type particulate scrubbers will have the captured material contained on or in the droplet, which clearly must be caught. The use of, for example, limestone slurries to remove SO_2 introduces particulate matter into the spray, making it imperative to use demisters, another word for entrainment separators. Calvert, et al. at APT, Inc. undertook a detailed examination of the state of the art in entrainment separators, the interim report for which was issued in October 1974.[24]

Goals

The scope of work defined by IERL-RTP for Contract 68-02-0637 was, in essence:

1. Evaluation of demister technology, including the existing data and theory with an emphasis on identifying problem areas
2. Experimental investigation of the performance of the various types of entrainment separators, studying the efficiency, pressure drop, reentrainment, plugging, face velocity, etc.
3. Development of improved methods and equations for the selection and design of entrainment separators
4. Pilot test of promising new designs
5. Recommendations concerning research and development for improving demisters

Methods

A literature survey was conducted, directed toward the subjects of primary collection efficiency, pressure drop, reentrainment, problems of entrainment separators, and detailed information on presently-used separators. This included visits to libraries, a computer search in the APT library, contacts with manufacturers, and visits to EPA and TVA facilities.

In the theoretical part of the program, equations predicting primary collection efficiency and pressure drop were acquired for various types of entrainment separators, including cyclones, packed beds, tube banks, knitted mesh, and sieve plates. Mathematical models for primary efficiency and pressure drop in a zigzag baffle separator were also developed, and models for reentrainment in cyclones and in horizontal and vertical baffles were discussed.

The experimental part of the program consisted of three parts. In one part, a small-scale experiment was conducted to observe the transition from separated flow to separated-entrained flow, with special attention to the effects of duct dimensions, dependence of entrainment velocities on liquid flow rate, drop size distribution, and impingment angle between air and water phases. For this purpose a two-phase flow system was constructed, consisting of an inclined, fixed channel through which a film of water flowed, and an adjustable nozzle through which air could be blown to impinge at chosen angles on the water film. Visual observation and a filter paper technique were used to determine the transition from separated to separated-entrained flow.

In a second part of the experimental program, a pilot plant was designed and built for the study of entrainment separators. Its purpose was to obtain data to check design equations for efficiency of separators and to study effects of gas velocity, liquid drainage and flooding, and vertical and horizontal sections. The pilot plant capacity was 1.4 m^3/s or 3 x 10^3 cfm. Five different types of entrainment separators were studied:

1. Knitted mesh (Model 4CA, layered, crimped in alternate directions, 0.144 g/cm^3 density, 0.028 cm wire diameter, 98.2 percent voids, 2.8 cm^2/cm^3 mesh surface area, 10 cm thickness, and AISI 304 material)

2. Packed bed (2.5 cm Pall ring packing, 1.9 cm^2/cm^3 specific surface, 0.088 g/cm^3 density, 30 cm bed length, and polypropylene plastic material)

3. Zigzag baffle section (7.5 cm x 61 cm x 0.16 cm dimensions, six rows, 2.5 cm spacing between rows, 30-degree angle between baffle surface and air flow direction, and 7.3 cm spacing between baffles in a row)

4. Cyclones (61 cm diameter x 243 cm high, 30.5 cm long x 15 cm wide inlet, 30 m/s maximum inlet velocity)

5. Tube bank (six rows, 1.9 cm external diameter, 61 cm length, and eight equispaced tubes in a row)

The ranges of variables were:

Drop diameter = 82 to 1600 μm

Air velocity = 100 to 750 cm/s

Liquid flow rate = 17 to 670 cm^3/s

Air flow rate = 0.13 to 1.4 m^3/s

Results

In the theoretical part of the program, design equations were given for entrainment separators. Specifically, formulas for primary efficiency are exhibited for cyclones, packed beds, knitted mesh, sieve plates, and zigzag baffles; they have the form

$$E = 1 - \exp\left[- f\ (K_p)\right] \qquad (5)$$

where K_p is the droplet inertial impaction parameter, and f is a function of this parameter. For packed beds, sieve plates, and zigzag baffles, f is linear; for the other separators, f is nonlinear, increasing with K_p. For a tube bank, the exponential term in Equation (5) is replaced by

$$(1 - C\eta)^n \tag{6}$$

where η is the target efficiency of a rectangular aerosol jet, C is a geometric factor, and n is the number of rows. As n tends to infinity, this expression tends toward the exponential form.

The design equations for primary collection efficiency were found to give values higher than the observed overall separator efficiency. This may have been due to reentrainment, one cause of which is high gas velocity. Usually, entrainment separators are operated at low gas velocity, leading to large sizes and costs. Rupture of bubbles at the gas-liquid interface, with subsequent drop formation, is the principal cause of reentrainment in sieve plates, bubble-cap plates, packed beds, and knitted mesh. Lower velocities inhibit such rupture.

Design equations were derived for reentrainment in cyclones. These equations gave lower reentrainment velocities than those observed experimentally.

Collection efficiency is plotted versus gas velocity in Figure 7 for horizontal flow through tube banks, for various inlet drop diameters. Penetration due to less than 100 percent primary efficiency was observed for velocities under 3 m/s. The slight drop in efficiency at 7 m/s may be due to reentrainment (not specifically alluded to by APT, Inc.). As gas velocity increases, efficiency first increases as the impaction parameter increases, then efficiency decreases as the gas velocity becomes high enough to reentrain the water.

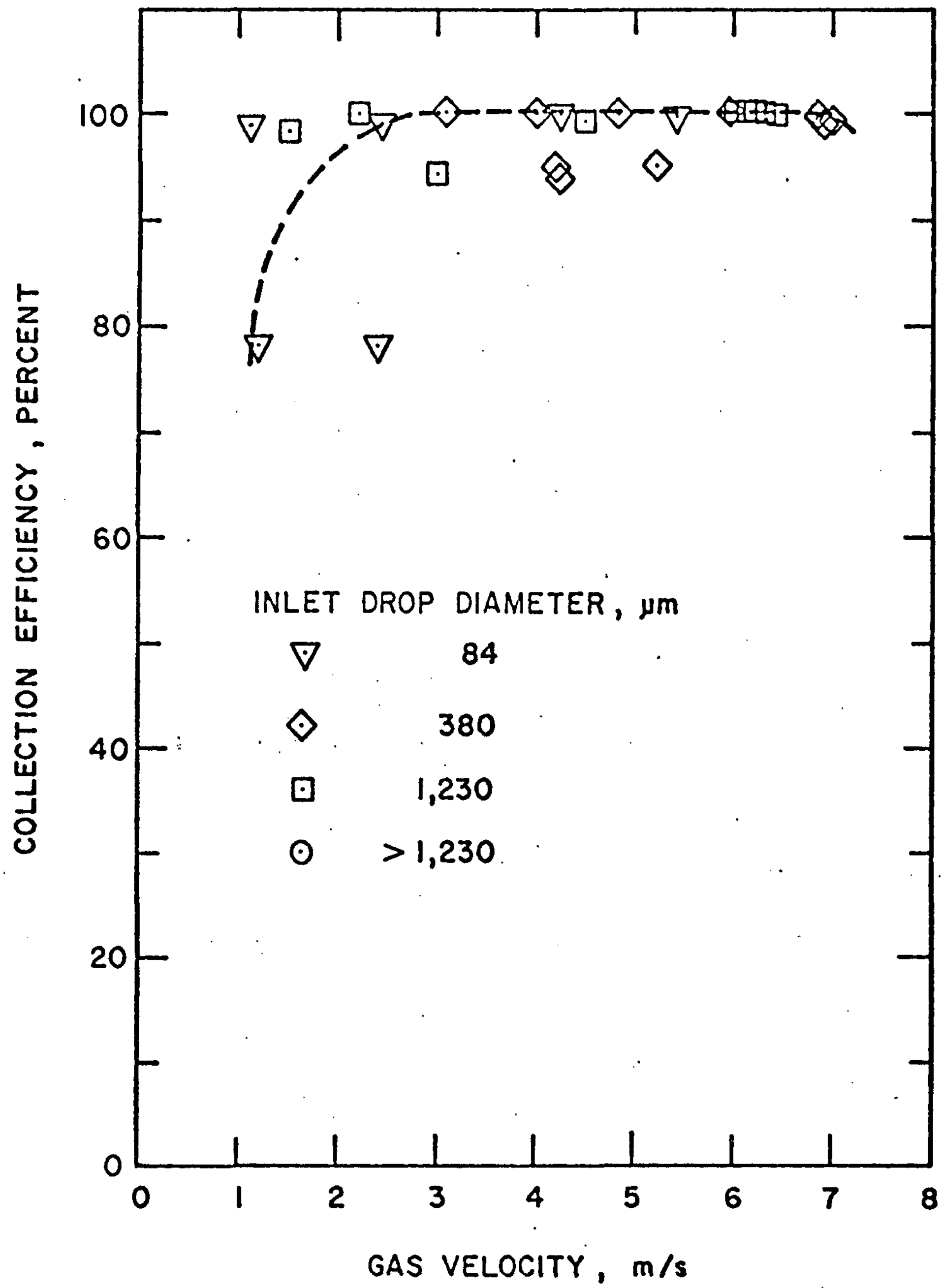


Figure 7. Collection efficiency versus gas velocity in tube bank.

In general, a minimum was observed in the drop size distribution of the reentrained drops. The minimum was generally in the range of 40 to 80 μm, with a few exceptionally high values up to 190 μm associated with baffle separators. Observed reentrainment velocities were much higher than those obtained by Kotov[37] in similar experiments.

Conclusions

The theoretical models for primary collection efficiency and pressure drop developed for baffles showed good agreement with experimental data. However, predicted reentrainment velocities in a cyclone were much lower than the experimental values.

The effect of liquid load on pressure drop was negligible in the packed-bed, zigzag-baffle, tube-bank, and cyclone separators. Collection efficiency in the experimental range was nearly 100 percent, with 0.5 to 1.0 percent reentrainment at high gas velocities. The mass-median drop size for reentrainment varied between 250 μm and 650 μm. The minimum drop size present in the reentrainment was 40 μm.

A problem with entrainment separators is the fact that the gas velocities are limited to low values by the onset of reentrainment and flooding conditions. Another problem involves solids deposition and consequent plugging.

Recommendations

Calvert et al. suggested that a further study is needed of:

1. Onset of reentrainment conditions,
2. Rate of reentrainment,
3. Equilibrium constant between entrainment and liquid film,
4. Drop size distribution,

5. Smooth and shock contact gas liquid, and
6. Effect of duct dimensions.

The new knowledge would be applicable toward improving design methods to determine reentrainment under operating conditions, the effect of high gas velocities, and improvements to reduce reentrainment.

It would be desirable to have insight into the mechanisms by which suspended and dissolved solids become deposited, so that this deposition could be minimized by appropriate design. Since some deposits are inevitable, research on methods of washing, etc. to remove them with a minimum expenditure of liquid is desirable. (Some small-scale experimental work was done as part of the third part of this program. More work is planned under other programs.)

Performance data on industrial entrainment separators are generally not available. The ususal assumption in evaluating overall performance of scrubbers is that the entrainment separators are 100 percent efficient; the liquid introduced in the scrubbers is assumed to be entirely removed by the separators; and the effects of sedimentation, bends in the duct, etc. are neglected. Hence, attempts should be made to collect performance data under industrial conditions; this will help in the future design of practical separators.

A demonstation plant should be built, of larger capacity (about 35×10^3 cfm or 170 m^3/s as compared with the present pilot plant capacity 3×10^3 cfm or 1.4 m^3/s).

Finally, combinations of entrainment separators should be studied with a view toward achieving higher efficiencies and/or lower capital costs.

WET SCRUBBER LIQUID UTILIZATION (Stanford Research Institute, September 1973)

Introduction

As interest in condensation effects in scrubbing intensified, this IERL-RTP program with Stanford Research Institute was modified to shift the emphasis from the study of the effects of energy consumption and water flow rate on efficiency to the effects of condensation. The scope of work included: literature review on water and power consumption as well as on condensation/evaporation effects; bench-scale study of co-current spray scrubber efficiency; recommendations for potential commercial uses of condensation in scrubbing, with emphasis on venturi scrubbers; development of plans for pilot-scale research.

Goals

The principal goal was the study of the effects of the following on collection efficiency of a venturi-type scrubber:

1. Power consumption per unit volume flow rate
2. Venturi orifice size (equivalently, gas velocity)
3. Liquid-to-gas ratio
4. Condensation/evaporation

Secondary goals were the literature review, recommendations for commercial applications, recommendations for pilot-scale research.

Methods

The experimental apparatus used by Semrau and Witham is shown in their report.[5] It allowed them to control the temperature and humidity of the gas to be scrubbed, the temperature of the scrubbing water, the aerosol concentration, and the relevant gas and liquid flows. The aerosol was produced by an ultrasonic nebulizer (Devilbiss Model 35 A) which atomized a solution of ammonium fluorescein to produce a spherical, nonhygroscopic aerosol that had a mass-median diameter (from electron microscopy) of about 0.6 μm. Inlet concentrations were about 10^{-3} g/m^3. Both inlet and outlet concentrations were measured by fluorimetric analysis of samples captured on Nuclepore filters.

During the investigation, the scrubber was fitted with three different orifices, having diameters 2.54, 3.81, and 4.45 cm. Air flows ranged from about 0.008 m^3/s (18 cfm) to 0.06 m^3/s (130 cfm) for the tests at ambient conditions done to investigate the impact of orifice size (gas velocity) and liquid-to-gas ratio (L/G) on efficiency. Various air temperatures and humidities were used to evaluate the influence of condensation/evaporation. Air and water characteristics were chosen to make four different sets of conditions:

1. Ambient conditions
2. Adiabatic saturation, with the water temperature at the wet bulb temperature of the gas to be scrubbed
3. Condensing conditions, with the inlet gas wet bulb temperatures well above the temperature of the scrubbing liquid, to promote condensation
4. Vaporizing conditions, with the gas at temperatures near those for the condensing conditions but quite dry to keep the wet bulb temperature was well below the temperature of the scrubbing water, thus promoting evaporation.

Results

The data were plotted as the natural logarithm of the number of "transfer units" (N_t) versus fluid power consumption per volume flow rate, also called "effective friction loss" or "contacting power" or "equivalent pressure drop," Δp (mmH_2O = mmWC). The penetration, Pt, is the ratio of the outlet to inlet concentrations:

$$Pt = m_2/m_1 \qquad (7)$$

The number of transfer units, N_t, is the negative of natural logarithm of the penetration:

$$N_t = -\ln Pt = \ln(Pt^{-1}) \qquad (8)$$

If the penetration has an exponential dependence on effective friction loss to the power a, then:

$$Pt = \exp(-b\Delta p^a), \qquad (9)$$

and the logarithm of the number of transfer units would be

$$\ln N_t = a \ln \Delta p + b. \qquad (10)$$

An exponential dependence on the effective friction loss, Δp, would be a straight line with slope a on a log-log plot.

Because the aerosol generator was not constant during the trials, despite considerable efforts to abate the variations, it was found that the variance of the data could be reduced if the aerosol generated at the high rates of generation ("aerosol A") was distinguished from that produced at low rates of generation ("aerosol B"), the boundary rate being about 750 μg/min. The aerosol (B) produced at the lower generation rates caused lower scrubber efficiencies at equivalent pressure drops than the aerosol produced at the higher rate, making it likely that aerosol B had a smaller mass mean diameter or was more polydisperse.

The report by Semrau and Witham[5] showed results of tests of scrubber performance as a function of effective friction loss (pressure drop across the venturi) for different throat velocities and different liquid-to-gas ratios. Figure 8 summarizes these. The power consumption

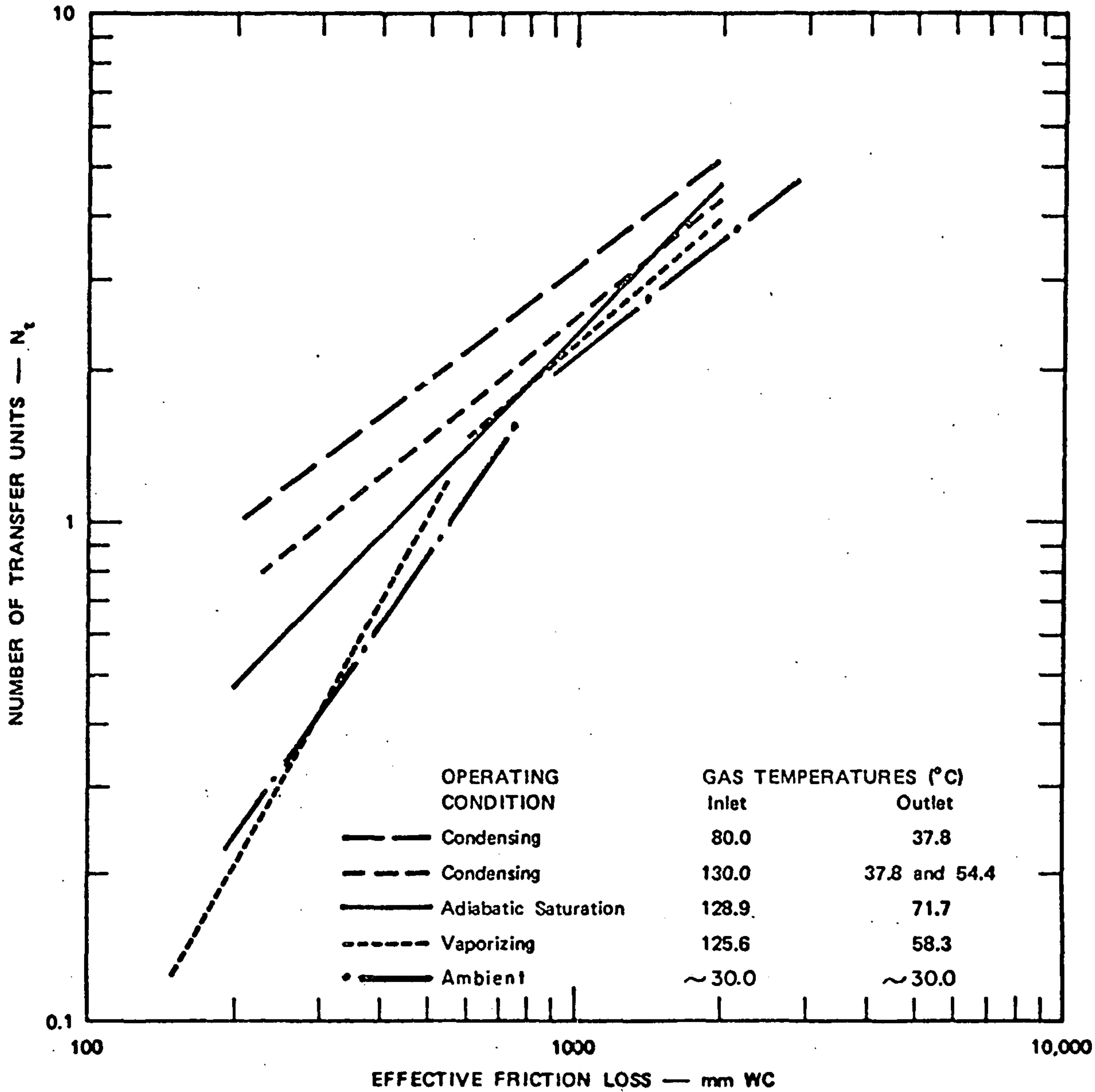


Figure 8. Summary of scrubber performance curves for adiabatic saturation, condensation, and vaporization scrubbing-aerosol B

was found to be much more important than the orifice (throat) velocity or the L/G ratio. (One reason this had to be established was that the later tests for condensation/evaporation effects had to be done at different L/G ratios.) At pressure drops larger than about 40 cm WC, the slope (a) is less than one, but below this pressure drop, the slope is greater than one. This shows "diminishing returns" from the higher pressure operation.

In certain cases, scrubbers in series may have a greater efficiency than a single scrubber with the same pressure drop. The penetration of two scrubbers in series, Pt_s, is the product of their individual penetrations, Pt_1 and Pt_2, but the power consumption is the sum of their individual power consumptions:

$$\Delta p = \Delta p_1 + \Delta p_2 \tag{11}$$

Two-stage scrubbing would give

$$Pt_s = Pt_1\ Pt_2 = e^{-b\Delta p_1^{\ a}}\ e^{-b\Delta p_2^{\ a}} \tag{12}$$

$$Pt_s = e^{-b(\Delta p_1^{\ a} + \Delta p_2^{\ a})} \tag{13}$$

For a single scrubber with the same pressure drop,

$$Pt = e^{-b\Delta p^a} = e^{-b(\Delta p_1 + \Delta p_2)^a}, \tag{14}$$

but for $a < 1$

$$(\Delta p_1 + \Delta p_2)^a < \Delta p_1^{\ a} + \Delta p_2^{\ a} \tag{15}$$

so

$$Pt > Pt_s.$$

In words, if a, the exponent of Δp, is less than one, two scrubbers in series will give less penetration (higher efficiency) than one scrubber with a pressure drop equal to the sum of their pressure drops. The comparison is more difficult when the slope a is a function of pressure drop, as it seems to be, and where the successive scrubber(s) in a series arrangement may follow somewhat different equations because of particle conditioning by the previous scrubber(s).

Figure 8 is adapted from Semrau and Witham.[5] It shows the effects of condensation and evaporation on the collection efficiency of the scrubber for aerosol B. (We have added the ambient data from another figure.) Table 5 summarizes the results. (Series III tests were run with the inlet gas only 5°C or so above the adiabatic saturation temperature, wet bulb temperature, "so that the tests approximated scrubbing of a presaturated gas.") The collection efficiency at a given pressure drop, or effective friction loss, was clearly better for the condensing situations than for the ambient or vaporizing conditions.

Conclusions

We quote directly from Semrau and Witham:[5]

- Over very wide ranges of gas velocity, liquid-to-gas ratio, and gas pressure drop, the collection efficiency of the scrubber was dependent only upon effective friction loss (essentially equal to the gas pressure drop) and independent of gas velocity and liquid-to-gas ratio (except as these latter factors affected gas pressure drop). (This conclusion did not apply in cases where vaporization or condensation effects were involved.) There may still be some independent effects of gas velocity or liquid-to-gas ratio at very low values of these variables, but if so, the operational region is not one of much practical significance.

- The size of the orifice gas/liquid contactor had no effect on collection efficiency, independent of effective friction loss.

Table 5. SELECTED COMPARISONS OF SCRUBBER PERFORMANCES AT DIFFERENT OPERATING CONDITIONS

Test Condition		Adiabatic Saturation		Condensing Series I and II		Condensing Series III		Vaporizing	
Gas Temp (°C) Inlet		129		130		80.0		126	
Outlet		71.7		54.4 and 37.8		37.8		58.3	
Aerosol	Effective Friction Loss (mm WC)	Transfer Units	Collection Efficiency (%)	Transfer Units	Collection Efficiency (%)	Transfer Units	Collection Efficiency (%)	Transfer Units	Collection Efficiency (%)
A	250	0.685	49.6	1.01	63.3				
	1000	2.52	91.95	2.93	94.66				
	1500	3.68	97.48	4.00	98.17				
B	250	0.583	44.2	0.840	56.8	1.14	67.8	0.303	26.0
	1000	2.30	90.0	2.46	91.46	3.12	95.55	2.20	88.9
	1500	3.43	96.76	3.36	96.50	4.18	98.47	3.05	95.23

- Condensation scrubbing of the test aerosol produced significant but not very large increases in collection efficiency at a given effective friction loss. The re-results were qualitatively similar but quantitatively much less than indicated by earlier pilot-plant studies of condensation scrubbing of Kraft recovery furnace fume under similar operating conditions.

- Cooling the outlet gas below 54°C did not increase the condensation scrubbing effect measurably, presumably because only a small additional quantity of water vapor was condensed.

- Adjusting the inlet gas to a nearly saturated condition before contacting with cold water markedly improved the effectiveness of condensation scrubbing.

- Vaporization of scrubbing water tended to reduce scrubber collection efficiency, particularly in the lower range of effective friction loss.

- In practical cases, condensation collection is not an alternative to conventional high-energy scrubbing, but is a supplement that can reduce the scrubbing energy requirements to a greater or lesser degree. Promoting diffusional mass transfer (such as vapor condensation) in practical equipment also requires energy for gas/liquid contacting.

- Because of the requirements for water cooling and possible gas humidification, the net saving of energy in condensation scrubbing may not often outweigh the other associated costs.

- Condensation scrubbing may be, and probably is, warranted under the following conditions:

    - Where the waste gas already has a high water vapor content and there is use for low-level heat in the associated process system (e.g., Kraft pulp mills).

    - Where the gas must be cooled and dehumidified anyway, for process reasons (e.g., cleaning of blast furnace gas; purification and conditioning of feed gas to contact sulfuric acid plants).

Recommendations

Semrau and Witham of Stanford Research Institute recommended that similar work be extended to aerosols of other mean particle sizes to investigate size dependence. They also suggested that the decrease in efficiency at the low equivalent pressure drop range be studied further. More work was urged regarding two other types of scrubbers: those for which the scrubbing liquid supplied the power and those for which a mechanically driven rotor supplied power to mix particles and drops. If a field demonstration of condensation scrubbing was to be done, they recommended that it be done on a Kraft recovery furnace fume, a possible commercial application.

PILOT SCALE DEMONSTRATION OF CHARGED DROPLET SCRUBBING (TRW SYSTEMS, INC. 1972-1975)

In previous work, TRW demonstrated that charged droplet scrubbing (CDS) was feasible to aid fine particle removal. The present study is to construct and evaluate a pilot scale demonstration of charged droplet scrubbing. TRW's responsibilities included site selection, verification of hardware, and actual testing of the CDS device. The IERL-RTP project description laid down the following goals and guidelines for the project:

> "TRW shall demonstrate a charged droplet scrubber (CDS) with a capacity of at least 25,000 cfm on an industrial source. TRW shall collect particulate data to include particle size distribution at inlet and outlet, fractional efficiency, Ringleman readings at exit with and without CDS operation, and particulate concentration at inlet and outlet. TRW shall record all relevant process data, including gas humidity, temperature, velocity, and water flow rates, temperature, pH, and conductivity for inlet and outlet. The CDS shall be operated continuously for at least 500 hours. The final report shall contain a comprehensive summary of test procedures and analysis of results, a discussion of fractional efficiency, limitations, advantages, etc. and a cost estimate of a full-size application."

SYSTEMS OF CHARGE DROPLETS AND PARTICULATES (MIT)

Under a contract with IERL-RTP, Melcher and Sachar[8] of MIT studies experimentally and theoretically the various combinations of charged droplets and particles which might be used in electrostatically augmented spray scrubbers. They defined characteristic times for certain particle and droplet behavior, and from these characteristic times the collection efficiency of such a system could be determined. They confirmed their theoretical predictions experimentally. Their group t_{res}/t (ratio of residence time to characteristic time for collection) is essentially the same as our wA/Q. The characteristic times all have the form:

$$t^* = 1/4\pi q\ q\ B\ N$$

where q is charge, B is mobility, and N is number concentration. The motion of particles (subscript p) with respect to themselves is characterized by:

$$t_p = 1/4\pi q_p^{\ 2}\ B_p\ N_p$$

The motion of droplets (subscript d) with respect to themselves is characterized by:

$$t_d = 1/4\pi q_d^{\ 2}\ B_d\ N_d$$

The motion of particles with respect to droplets is characterized by:

$$t_{dp} = 1/4\pi q_p\ q_d\ B_p\ N_d$$

These times are the average distance between the objects in motion divided by their migration velocity, as calculated from the Coulomb force at the average distance. The characteristic collection time for mutual repulsion by particles is t_p. The characteristic collection time for collection of the particles by the droplets (and for mutual repulsion if polarities are the same) is t_{dp}. The characteristic time for mutual repulsion of the spray droplets is t_d; it must be substantially longer than the characteristic collection time if it is not to limit collection. The approach of Melcher and Sachar unified the analysis of many seemingly diverse systems which involved charged particles and charged droplets.

DESIGN AND FABRICATION OF MOBILE WET SCRUBBER FACILITY (NAVAL SURFACE WEAPONS CENTER, 1973 TO 1975)

Information was needed on the suitability of scrubbers to various particulate sources. Responding to this need, by an interagency agreement IERL-RTP contracted with the Naval Surface Weapons Center (NSWC) to design, construct, and initially test a mobile wet scrubber pilot facility. NSWC was charged with testing the mobile scrubber on selected sites before turning over the unit to IERL-RTP. The specific requirements for the effort according to IERL-RTP project description were:

> "NSWC will perform an evaluation of existing scrubber technology to develop the design for a mobile wet scrubber unit to be mounted on a flat bed trailer. NSWC will specify, procure and/or fabricate all equipment required to construct the unit. A plan for testing the unit will be prepared and tests will be carried out on specified sources prior to releasing the unit to IERL-RTP."

FOAM SCRUBBING FOR FINE PARTICLE CONTROL (MONSANTO RESEARCH CORPORATION, 1973 TO 1977)

The use of foam as the capture agent in a scrubber had long been discussed and the unit-operations were presented in the <u>Scrubber Handbook</u>.[4] IERL-RTP contracted with Monsanto Research Corporation (MRC) to conduct a small-scale feasibility demonstration of foam scrubbing. The mechanism of bubble formation and destruction and identification of operating characteristics of the scrubber system were to be primary targets of the study. The IERL-RTP project description "Scope of Work" to MRC read:

> "MRC shall conduct a preliminary investigation of foam scrubbing to identify and verify by experiment mechanisms for foam generation, particle capture, and foam destruction. The foam scrubber will likely consist of three components: the foam generator, particle collector, and foam destroyer. The preliminary study will determine the minimum energy requirements for foam breaking and will attempt an economic analysis of foam scrubbing. The second phase of work will involve the verification of fine particle collection. This will include study of foam generation to determine surfactant type and concentration, and bubble thickness and diameter; mechanisms for foam destruction; to develop and execution of a test to determine particle collection efficiency for a 500 cfm (minimum) capacity scrubber; and to evaluate the results of the testing. The final report shall contain summaries of the collection efficiencies, the operation, and the commercial applicability of the device."

GROWTH OF FINE PARTICLES BY CONDENSATION (SOUTHERN RESEARCH INSTITUTE, 1973 TO 1974)

The increased efficiency noted in the first FF/C work led IERL-RTP to contract with Southern Research Institute (SoRI) to "determine the feasibility of fine particle control systems based on growing fine particles by condensation and collection of the grown particles and to provide the data necessary to design such fine particle control systems." A complementary objective of the contracted study was to evaluate the use of vapor condensation in conventional particulate control devices to improve their collection efficiency. SoRI's objectives in the study were specified in the IERL-RTP project description:

> "SRI will perform experimental studies to determine the gas phase conditions necessary to grow fine particles to collectable size by water vapor condensation, the practicality of various methods of producing the required conditions, and the collectability of the grown particles by such conventional devices as ESP's and low energy scrubbers. Research will include investigation of the response by particle growth mechanisms to varying particle size distributions and to the chemical composition of the gas and particulate."

EVALUATION OF ARONETICS TWO-PHASE JET SCRUBBER (SOUTHERN RESEARCH INSTITUTE, 1974)

Introduction

As part of a program to investigate novel fine particle collectors, Southern Research Institute (SoRI) conducted for IERL-RTP tests of fractional and overall mass collection efficiency on the two-phase jet scrubber of Aronetics, Inc. Tests were performed on a full-scale scrubber used for controlling particulate emissions from a ferro-alloy electric arc furnace. The Aronetics device utilizes high pressure (~24 atm) hot water (~200°C) to produce a high velocity two-phase flow in a venturi nozzle (Figure 9). The scrubbing water may be heated by an economizer connected with the heat source of the industrial process. Alternatively, steam generated by high temperature off-gases ($> 650^{\circ}$C) may be used in an intermediate boiler to produce the hot water.

Goals

The objectives of the SoRI evaluation were:

1. Determine collection efficiency as a function of particle diameter.
2. Evaluate economics of the scrubber operation.
3. Determine optimum operating conditions.

Methods

Tests were performed with the Aronetics scrubber on a 7.5 megawatt submerged arc ferroalloy furnace at Chromasco, Inc.'s Memphis, Tennessee facility. Furnace operation was 24 hours a day with tapping done at 2 hour intervals; stoking and charging occurred at irregular intervals between taps. The variable cycle was accompanied by a variable emission rate which complicated the testing.

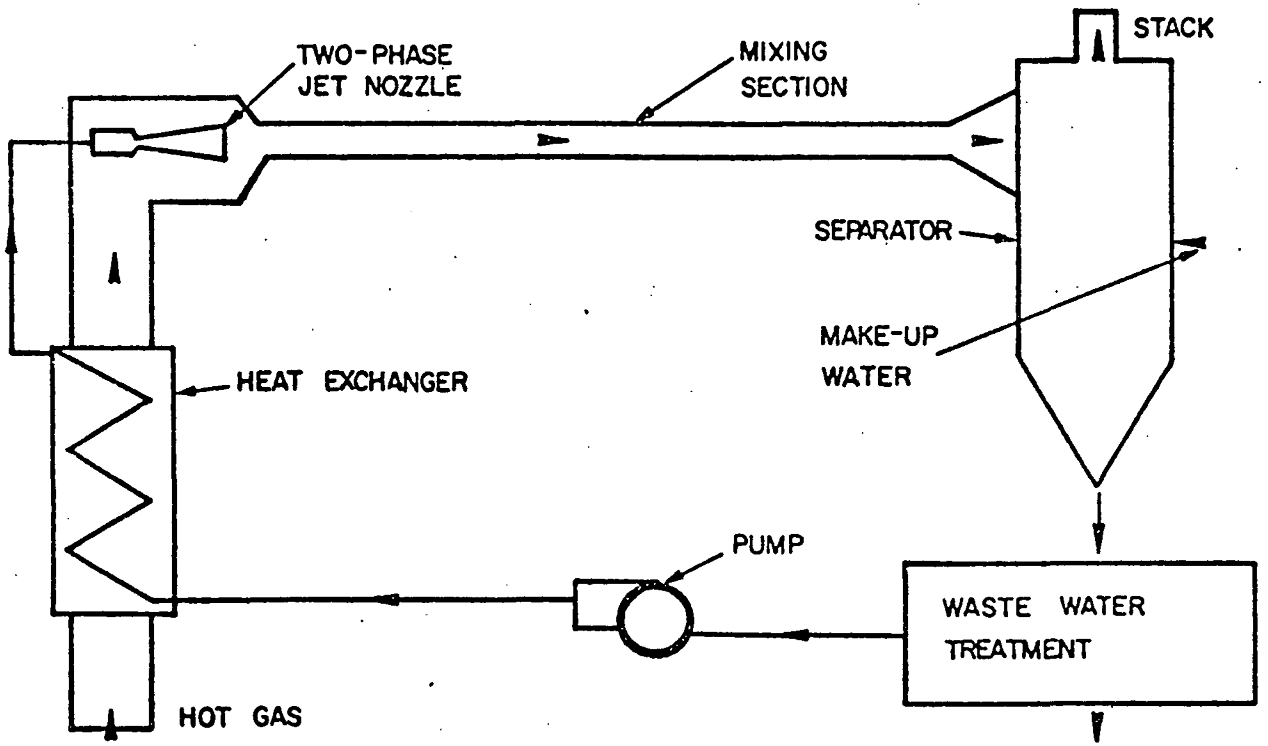


Figure 9. Generalized two-phase jet scrubber system

Particle measurement techniques used were:

1. Condensation nuclei counters and diffusion batteries for concentration and size distribution by number for $d_p < 0.2$ μm. (Extensive dilution, 65:1, was required.)

2. Optical techniques for concentrations and size distributions for $0.3\ \mu m \leq d_p \leq 1.5\ \mu m$.

3. Standard mass train measurements for total inlet and outlet mass loadings.

Results

Figure 10 indicates the fractional efficiency of the Aronetics scrubber based on reduced optical, diffusional, and impactor data. Total mass collection efficiencies of approximately 96 percent were determined by Guardian Systems, Inc. (Anniston, Alabama) under subcontract with SoRI.

Conclusions

The conclusions of SoRI were stated concisely in their final report:

> "The collection efficiency of the Aronetics Two Phase Scrubber determined by conventional (Method 5) techniques on a source producing particulate having a mass mean diameter of about 3 μm was 95.1 and 96.7 percent for two days of testing. Measured fractional efficiencies were about 70 percent at 0.01 μm, about 35 percent at 0.05 μm, 35 percent at 0.1 μm, 99 percent at 0.5 μm, 99 percent at 1 μm, and 99.4 percent at 5 μm. The scrubber energy usage during the tests was approximately 635 joules/1000 scm (17,000 Btu/1000 scf) at a net pressure rise of 12-1/2 to 16 in. H_2O. This energy usage was a result of using all the process waste heat available and may have been in excess of the minimum amount required to achieve the efficiencies obtained during these tests."

It should be noted that the thermal energy consumption, 17,000 Btu/1000 scf (= 6.3×10^5 J/m^3), is 400 hp/1000 hp/1000 cfm or 6300 cmWC equivalent pressure drop. In addition, SoRI evaluated the costs attending the scrubber operation based on 1967 factor and fuel costs and found annual direct operating costs per scfm:

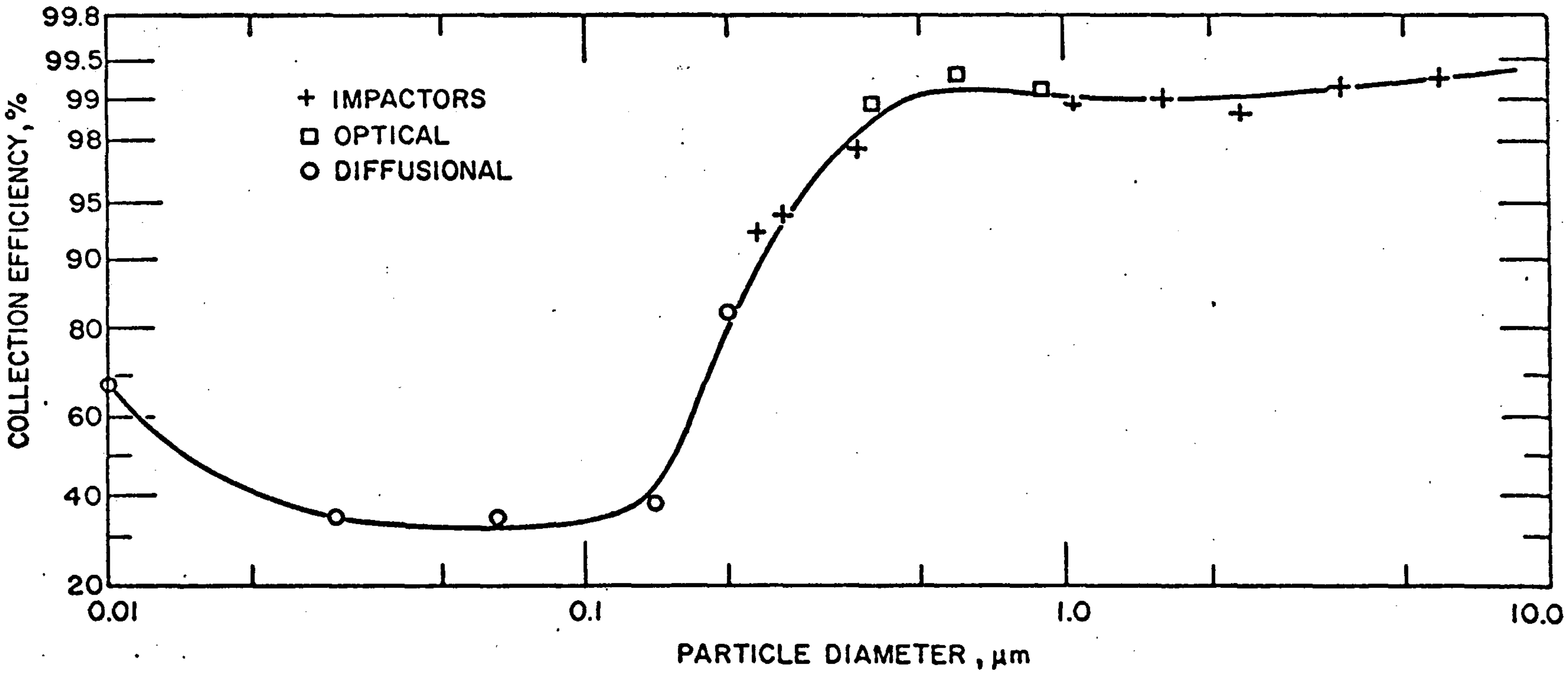


Figure 10. Fractional efficiency of the Aronetics Scrubber based on optical, diffusional, and impactor data

$1.016/scfm - year ($2,085/(m^3/s)-year) when waste heat can be used.
$5.59/scfm - year, ($11,843/(m^3/s)-year) when fuel for heating water must be purchased.

Excluding electric power used for fans and blowers, if the jet flow induced by the hot water suffices, the above costs became $0.042 and $4.44, respectively. These figures can be changed to approximate 1975 values by multiplying them by the ratio of the Marshall and Stevens price indices for the years 1975 (first quarter) and 1967: (437)/(263) = 1.66.

EVALUATION OF THE LONE STAR STEEL STEAM-HYDRO AIR CLEANING SYSTEM (SOUTHERN RESEARCH INSTITUTE, 1974)

Introduction

In another novel device evaluation, IERL-RTP contracted with Southern Research Institute (SoRI) to evaluate the Lone Star Steel Steam-Hydro air cleaning system designed to control particulate emissions from an open hearth furnace. The Lone Star device incorporates a high speed steam drive with injected water to accomplish scrubbing. The no moving-parts device consists of a steam nozzle, water injector, mixing tube, and twin cyclones.

Goals

Determine fractional and overall mass-efficiency of the Lone Star scrubber.

Methods

SoRI tested the performance of seven Lone Star scrubber modules fed by effluent from four open hearth steel furnaces, each producing three 300 ton (273 x 10^3 kg) batches of steel per day. Particulate measurements were made over a 1 week period at scrubber inlet and outlet ports using the following instruments and techniques:

1. Condensation nuclei counters and diffusion batteries for number concentration of $d_p < 0.2$ μm particles.

2. Multi-channel optical counter for concentration and size distribution for $0.3 \ \mu m \leq d_p < 1.5$ μm particles.

3. Cascade impactors for concentration and size distribution by mass for $0.25 \ \mu m \leq d_p \leq 5$ μm particles.

4. EPA Method 5 mass train measurements for total mass loading.

Sample dilutions of 500:1 at inlet and 65:1 at outlet were required for the optical and condensation nuclei instruments. Tests were conducted at different steam pressures, gas flow rates, and cyclone positions. SoRI indicated that direct comparison of data between specific tests would not be meaningful due to the variable cycle of the open hearth process.

Results

A summary of the averaged fractional efficiencies was provided in SoRI's final report and is reproduced here (Figure 11). The particulate source had a mass mean diameter about 1 μm. The overall mass collection efficiencies for each of the two days of tests were 99.90 percent and 99.84 percent, respectively. Lone Star's estimated energy requirements for scrubber operation at the latter efficiencies were 8250 to 12,750 Btu/1000 scf for pressure drop of 1 to 6 inches of water. This power consumption is 200 to 300 hp/1000 cfm or about 4000 cmWC equivalent pressure drop, 4×10^5 J/m^3.

Conclusions and Recommendations

No conclusions regarding optimum scrubber operating conditions were made by SoRI, and no recommendations for further testing and development were put forth.

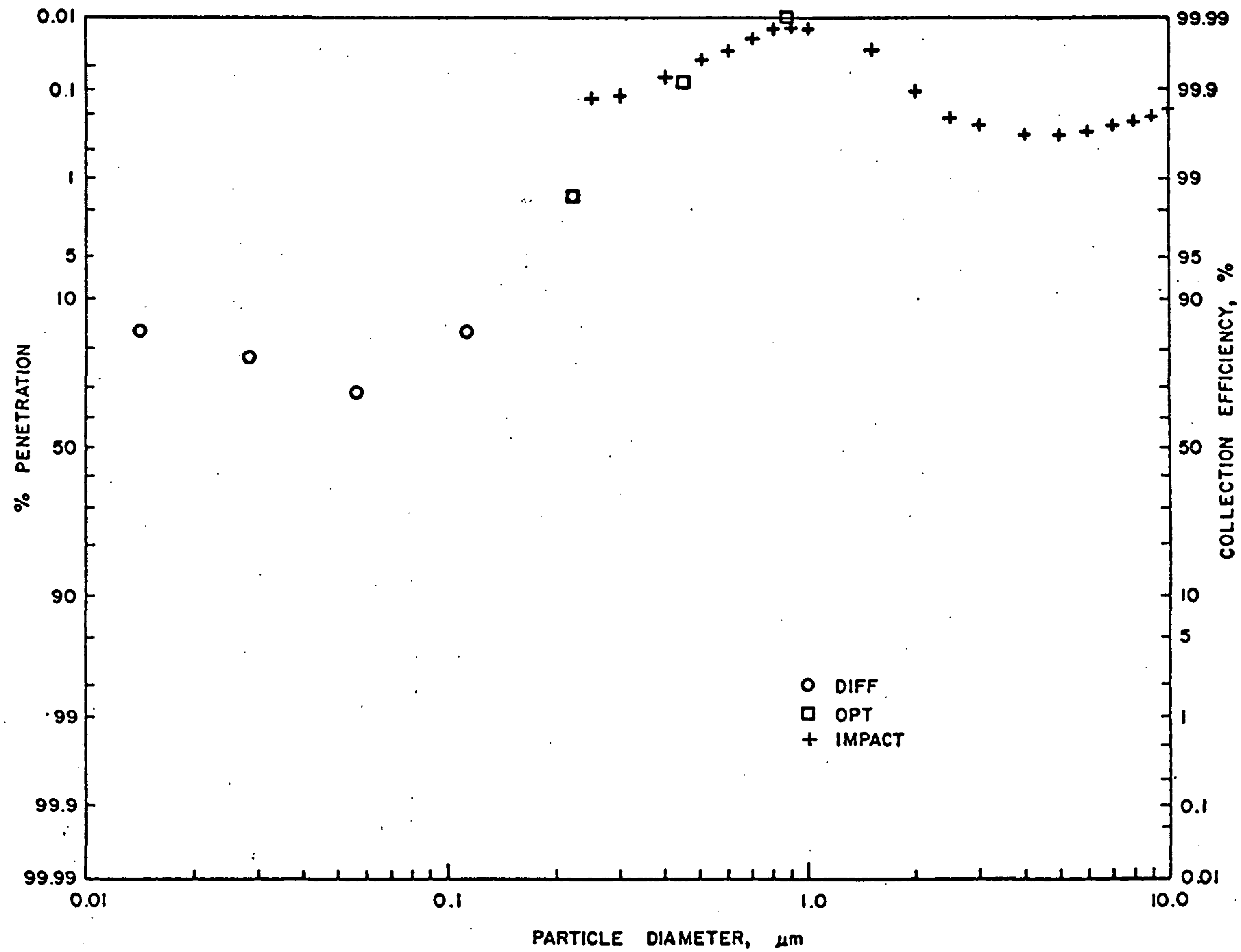


Figure 11. Fractional efficiency of the Lone Star Steel Steam-Hydro scrubber

DYNACTOR SCRUBBER EVALUATION (GCA, 1974)

Introduction

As part of IERL-RTP's program for evaluation of novel types of scrubbers, GCA tested a 1000 cfm (0.47 m^3/s) version of RP Industries' Dynactor, a scrubber design based on aspirative pumping. Figure 12 is a cross-section of a single-stage Dynactor diffusion contactor. The reaction column is typically 6 feet (2m) long, and is 12 inches (0.3m) in diameter. The liquid is atomized under high pressure, into a shower of high-velocity droplets, using a proprietary nozzle design. This shower of droplets educts large volumes of gas while simultaneously scrubbing it. The gas enters at ambient pressure and low velocity. Contact between gas and liquid occurs throughout the reaction chamber.

Goals

As in other evaluations, the objective of this study was to test a novel device purportedly capable of high-efficiency collection of fine particles. The testing included measurements of power consumption and fractional collection efficiency:

- At three flow rates
- At two temperatures
- At two dust loading levels
- For two different kinds of dust

Methods

The test methods were state-of-the-art techniques for measuring collection efficiency as a function of particle size using cascade impactors upstream and downstream from the scrubber. The data were analyzed using an F-test analysis of variance to determine what factors have a significant influence on collection efficiency in the various aerodynamic size

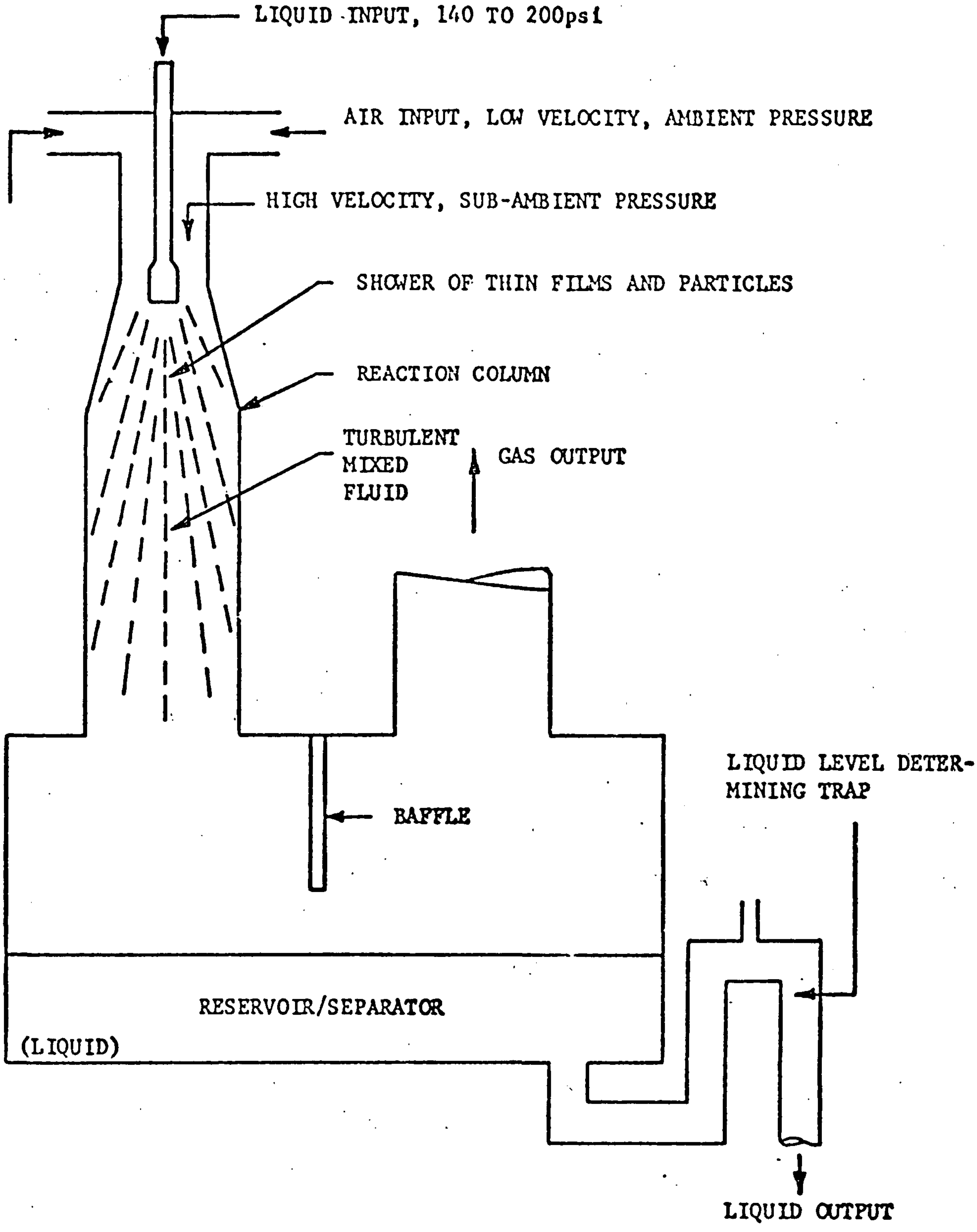


Figure 12. Single-stage Dynactor diffusion system cross-sectional view

fractions and to estimate experimental uncertainty. Pitot tubes were used to measure flow rates, and Magnehelic pressure gauges to measure pressure gain or drop.

The following measurements were made:

- Air flow and pressure gain versus spray nozzle pressure
- Electrical power consumption versus spray nozzle pressure
- Mass collection efficiency versus aerodynamic particle diameter for fly ash and iron oxide dusts at two values each of flow rate, temperature, and concentration

Results

Some of the principal results are shown in Figure 13 and 14, where collection efficiency is plotted versus particle aerodynamic diameter. Figure 13 shows the effects of loading and dust type, and Figure 14 shows the effects of flow rate and inlet temperature.

Conclusions

Efficiency is found to be greater for:

- Lower flow rate
- Lower temperature
- Higher dust concentration
- Fly ash than for iron oxide

Except for the temperature variation measurements, the differences were statistically significant for most size fractions.

From its aerodynamic cut diameter versus power per unit volume flow rate, it is found that the Dynactor Scrubber is essentially equivalent in power consumption to a well-designed venturi scrubber of the same collection efficiency.

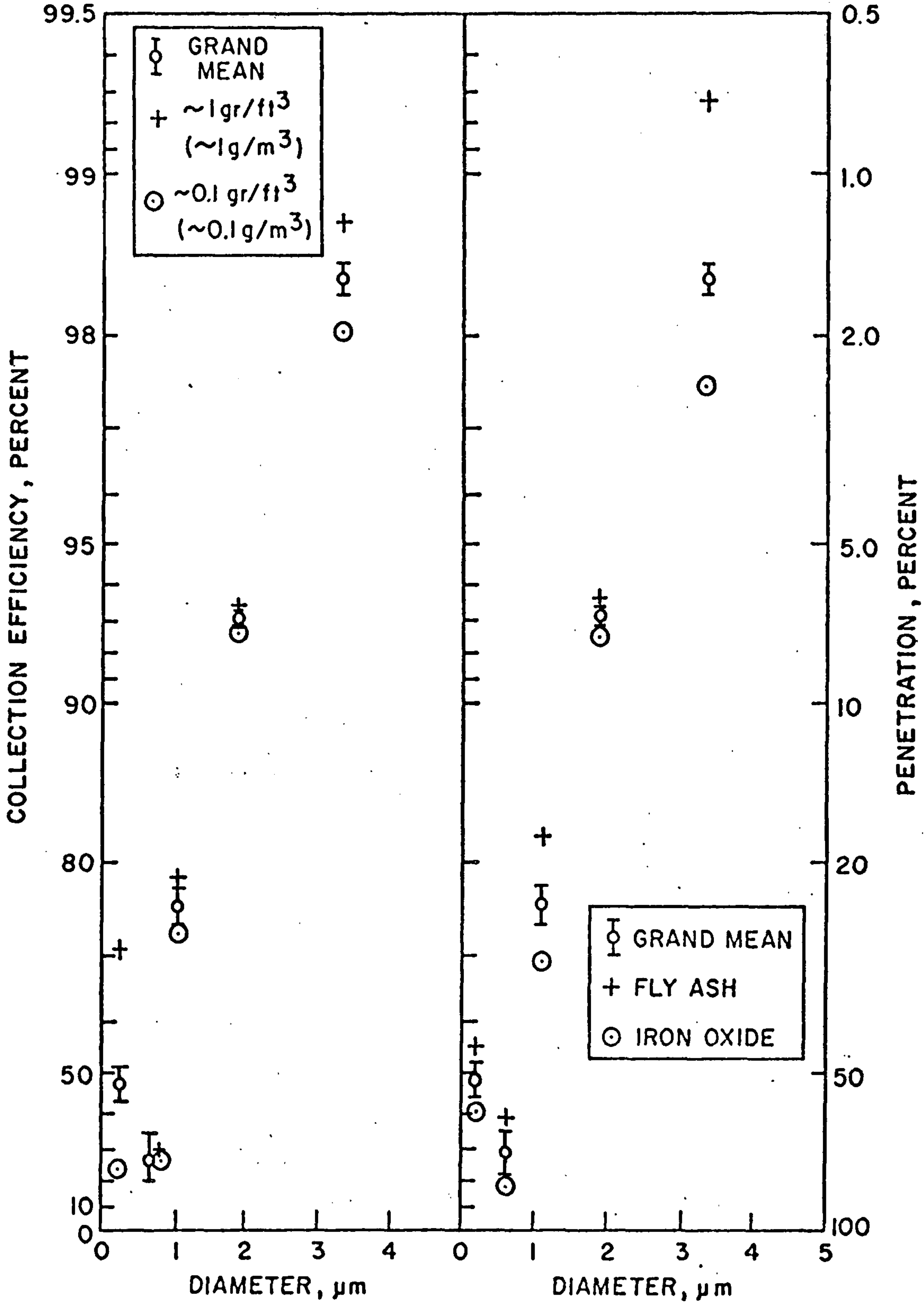


Figure 13. Dynactor scrubber collection efficiency versus particle aerodynamic diameter, effects of loading and dust type

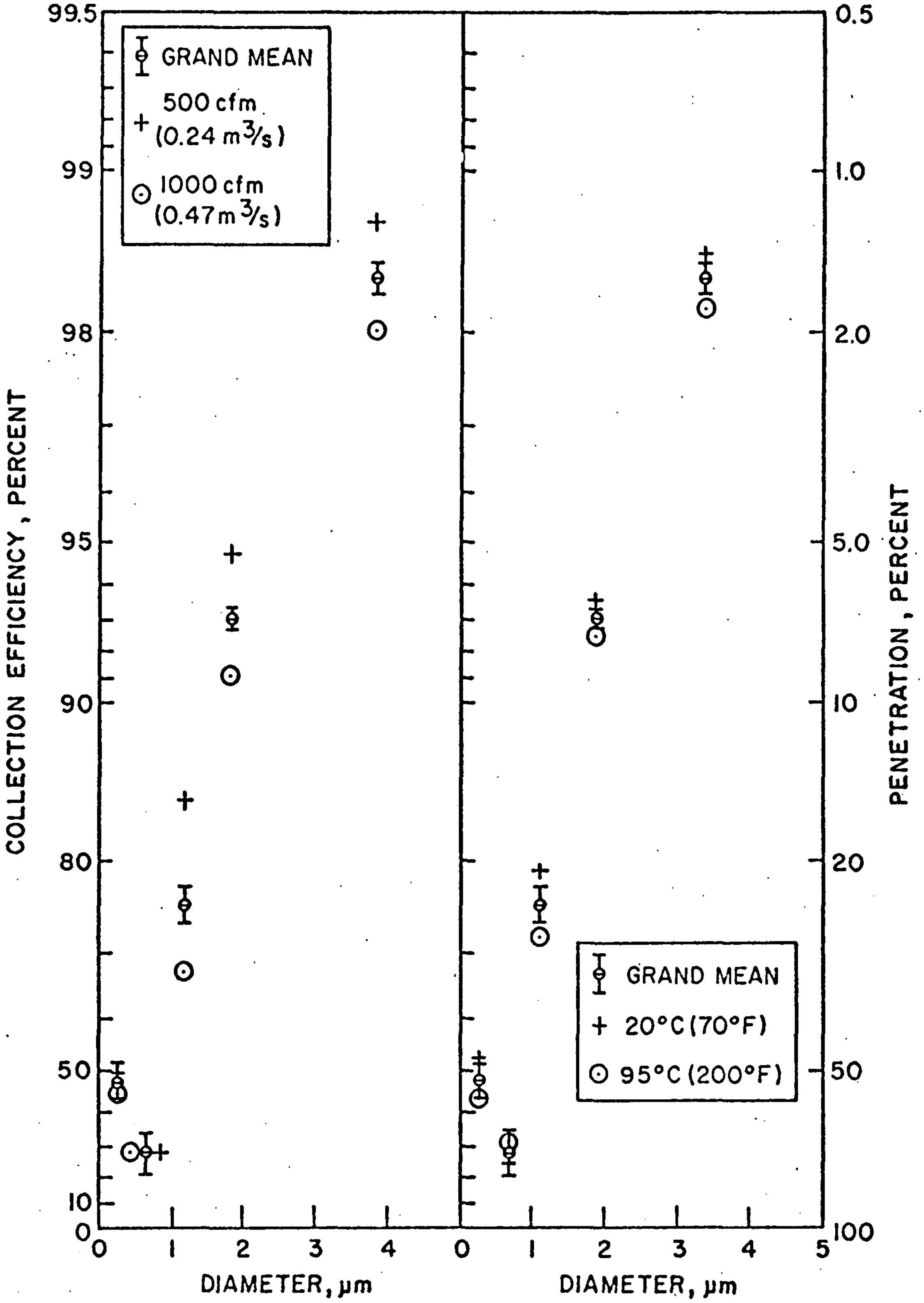


Figure 14. Dynactor scrubber collection efficiency versus particle aerodynamic diameter, effects of flow rate and inlet temperature

PENTAPURE IMPINGER™ EVALUATION (GCA, AUGUST 1974)

Introduction

Sponsored by IERL-RTP, an evaluation was performed by GCA/Technology Division on the "Pentapure™" scrubber of Purity Corporation. A gray iron foundry having a particulate effluent with a mass median aerodynamic diameter of 0.5 μm was the site of GCA's Pentapure performance tests. In the Pentapure scrubber dust-laden gas mixed with water spray is accelerated in a converging tube, after which the jet is impacted on a plate mounted perpendicular to the stream.

Goals

Evaluation goals were:

- Determine the collection efficiency as a function of particle aerodynamic diameter.
- Determine total mass collection efficiency.

Methods

The Pentapure Scrubber was installed after the spray-cooling section for the effluent gases in a grey iron foundry. Collection efficiency was determined by measuring particle mass concentrations at inlet and outlet of the scrubber. For total mass collection efficiency GCA used Method 5 total mass sampling traverses at inlet and outlet. Collection efficiency as a function of aerodynamic diameter was obtained with Andersen In-Stack Impactors up- and down-stream of the scrubber. A preimpactor for removing droplets larger than 15 μm diameter and heating tape to dry remaining drops were employed with each Andersen impactor. Comparison between experimental results and theoretical collection efficiency was carried out using formulae from the Scrubber Handbook.[4]

Results

- Total mass efficiency was 10 ± 2.5 percent.
- Particle aerodynamic diameter for 50 percent collection efficiency was between 2 and 4 μm. This agreed with theoretical predictions.
- Pressure drop across scrubber was 6 in. H_2O = 15 cmWC.

Conclusions

GCA noted that, "Measured efficiencies correspond to those expected from venturi scrubbers having somewhat less pressure drop. The Pentapure is not an efficient fine particle collector."

Recommendations

In its final report GCA stated:

> "The Pentapure scrubber does not give high efficiency for collecting fine particles and should not be investigated further for that purpose. In those situations in which a low-energy venturi scrubber would be suitable, the use of the Pentapure scrubber might be considered as well."

EVALUATION OF ELECTROSTATICALLY AUGMENTED PARTICULATE CONTROL DEVICES (GCA, OCTOBER 1974)

Nearing completion is a study by GCA/Technology Division of various applications of electrostatics to the control of fine particulates. The CSL-supported study encompasses electrostatic precipitators, filters, and scrubbers. It includes a review of the electrostatic force mechanisms, an analysis of programs in electrostatic augmentation supported by CSL, a checklist for electrostatic augmentation experimental work, and a method of setting control research priorities. A simplified method for predicting collection efficiencies in devices such as electrostatic spray scrubbers is presented, as well.

THEORETICAL EVALUATION OF THE CENTRIFIELD™ SCRUBBER (MIDWEST RESEARCH INSTITUTE 1974)

Introduction

The Centrifield™ Scrubber developed by the Entoleter Corporation was evaluated theoretically based on an idealized model by Midwest Research Institute (MRI) under IERL-RTP contract. The Centrifield scrubber achieves particle collection with a centrifugal vortex containing water droplets through which passes contaminated gas. The vortex is established by stationary vanes at the periphery which admit tangentially the gas and water spray. Large droplets are radially accelerated to pass through slots in the vanes, while smaller droplets exit at the core and must be deentrained.

Goals

The objective established by MRI was to evaluate the Centrifield scrubber with respect to its operating efficiency and economic feasibility.

Methods

The evaluation of the Centrifield scrubber by MRI proceeded as follows: An idealized scrubber model was formulated, assuming ideal, incompressible gas flow with a radial velocity that increased toward the core. Energy consumption by the radial vanes was calculated, but that used to accelerate the scrubbing droplets was assumed negligible. Certain assumptions had to be made about such system parameters as maximum water concentration in the vortex. Collection efficiency versus particle size was then calculated for several different pressure drops.

Results

Particle collection efficiency based on MRI's theoretical model of the Centrifield Scrubber is shown in Figure 15 as a function of diameter for

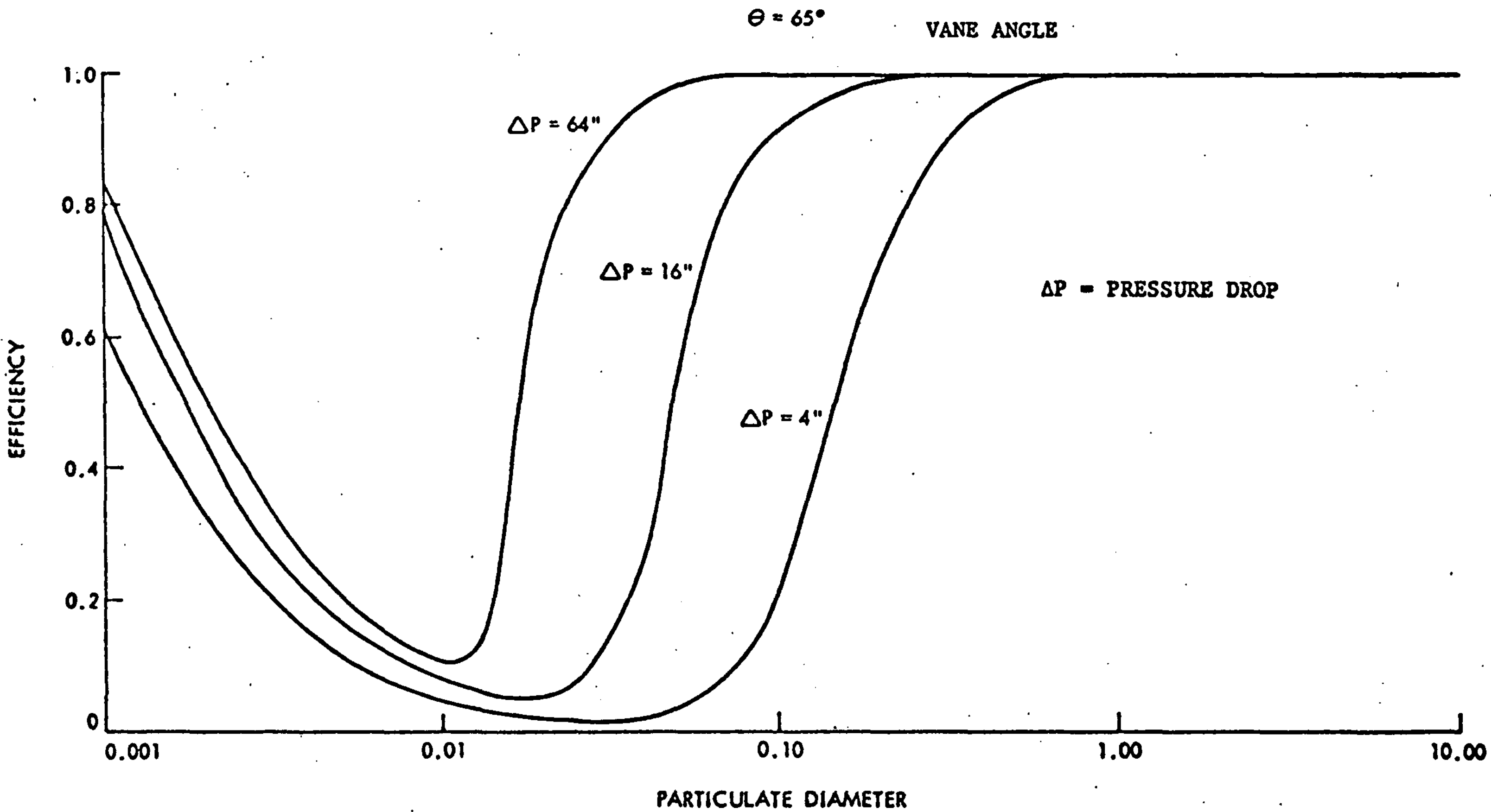


Figure 15. Fractional efficiency of idealized Centrifield™ scrubber (θ = 65)

the reasonable vane angle (with respect to tangential direction, 65°. The MRI report points out that the model is tentative because energy requirements for droplet formation were not considered and the droplet concentration is difficult to estimate. Since this is so, MRI indicates that Figure 15 must be viewed with a degree of skepticism.

Conclusions

1. Lower gas velocities and water feed rates compared to venturi scrubbers or other scrubbers may be possible.

2. It is not certain that the present device can operate at conditions necessary for the efficiencies of Figure 15.

3. It is impossible to make an economic evaluation of the device at present due to the uncertainty in collection efficiency.

Recommendations

The MRI report makes the following recommendations concerning further investigation of the Centrifield Scrubber:

"1. Additional operational data including the water concentration in the vortex, be obtained by the manufacturer. The drop size distribution would also be desirable;

"2. Operational data obtained in Item 1 be used as input into a simple model such as that presented in this report and estimated collection efficiencies determined; and

"3. If the estimated collection efficiencies obtained with actual equipment parameters are comparable to or exceed those for venturi scrubbers, the Centrifield Scrubbers should be tested under field conditions using approved EPA methods."

EXPERIMENTAL EVALUATION OF THE CENTRIFIELD™ SCRUBBER (SOUTHERN RESEARCH INSTITUTE, 1975)

Introduction

In an effort to get more definitive information on the performance of the Centrifield™ Scrubber, IERL-RTP contracted with Southern Research Institute (SoRI) to experimentally evaluate the performance of the device on an asphalt batching process. (This is included at this point, rather than in strict chronological order, for clarity.)

Goals

The goals of the study were to determine the total mass collection efficiency and fractional collection efficiency of the Centrifield™ Scrubber at a single plant installation.

Methods

The scrubber was attached to the asphalt plant following the plant's cyclone. Inlet and outlet particle concentrations and distributions of the scrubber were monitored using a diffusion battery, a multichannel optical counter, an electrical sizing device, a cascade impactor, and the standard EPA Method 5 measuring technique for total mass loading. The diffusional and optical measurements were made consecutively rather than similtaneously at inlet and outlet because only one set of instruments was available.

Results

Test averages of the size-dependent collection efficiencies were made and appear in the SoRI final report as Figure 16. To reduce the cascade impactor results a particle density of 2.5 g/cm^3 was assumed. According to SoRI, the scrubber energy usage during the tests was about

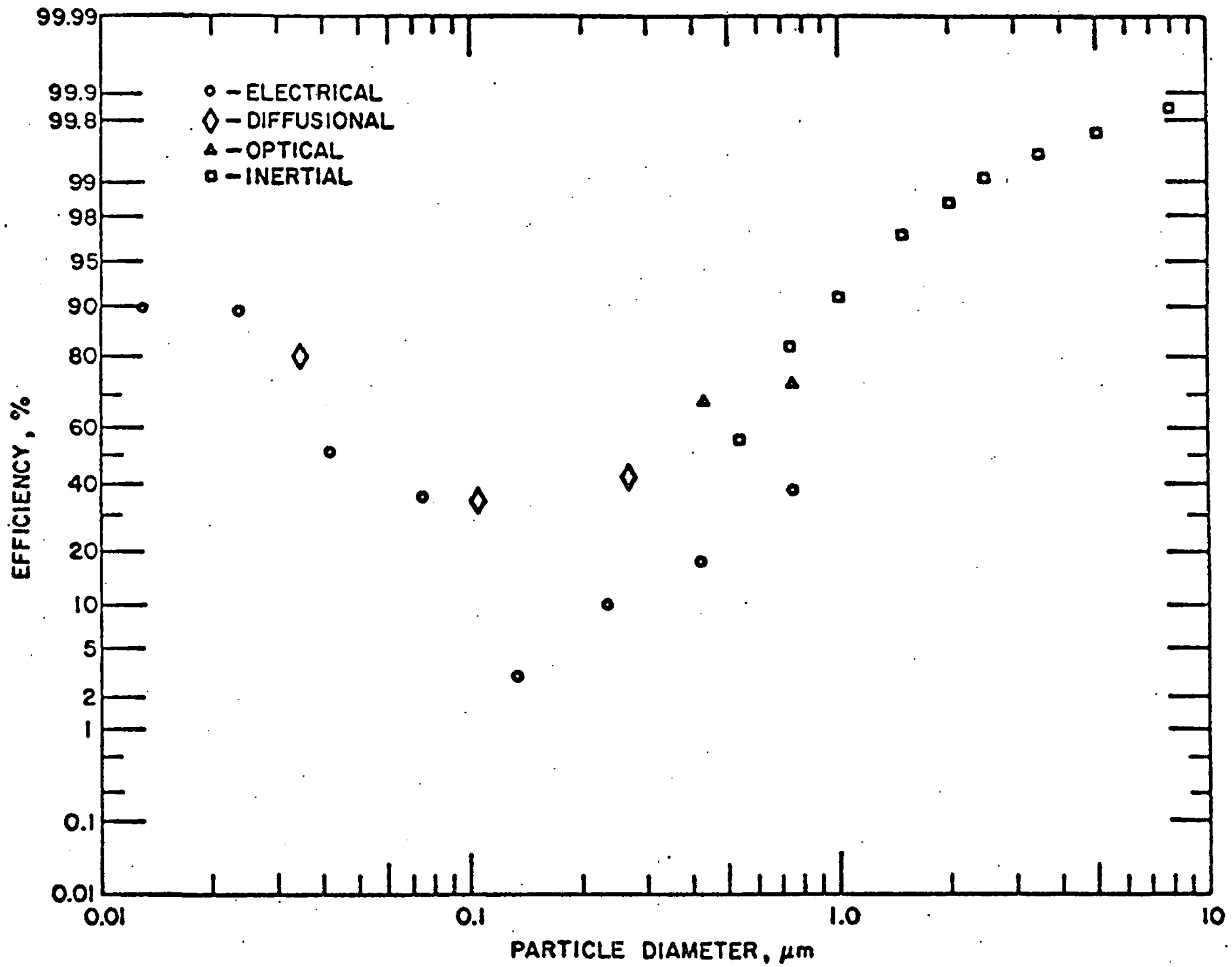


Figure 16. Fractional efficiencies as determined by the four methods used in the test program. The particle sizes shown for the impactor data are Stokes Diameters based on a particle density of 2.5 grams/cm^3

3 joules/1000 cm^3 at a pressure drop of 28 cm WC. The pressure drop 28 cmWC actually corresponds to 2.7 x 10^3 J/m^3 or 2.7 x 10^3 $W/(m^3/s)$ or 1.7 hp/1000 cfm; presumably the SoRI figure of 3 J/1000 scm is a mistake. Overall mass collection efficiency for the ~ 100 μm mass mean diameter source was 99.50 percent and 99.73 percent for the 2 days of testing. In addition SO_x collection efficiencies of 84 percent, 68 percent, and 88 percent on three tests were determined using H_2O_2 reagent in impingers.

Conclusions and Recommendations

SoRI offered no conclusions or recommendations beyond the test data.

FINE PARTICLE COLLECTION WITH UNIVERSITY OF WASHINGTON ELECTROSTATIC SCRUBBER (UNIVERSITY OF WASHINGTON, 1974 TO 1975)

The IERL-RTP studies done by TRW established the feasibility of charged droplet augmentation to improve the collection efficiency of scrubbers. It was then desirable to have a trailer-mounted mobile electrostatic wet scrubber for testing at coal-fired electric generating plants. IERL-RTP contracted with the University of Washington to build and field test such a portable scrubber. The project description read:

> "UW proposes to expand the technology gained from prior wet scrubber experience by building and testing a 1000 acfm portable scrubber. The UW wet electrostatic scrubber operates in the 120 to 200°F temperature range and is designed for the following characteristics: gas ΔP= -0.5 in H_2O, liquid to gas flow rate ratio = 1-5 gal/1000 acf, liquid ΔP= 40-80 psig (spray nozzles). Analysis of the data collected will be made to determine the design requirements for a larger (perhaps full-sized) electrostatic wet scrubber system. Simultaneous inlet and outlet measurements will be made of the gas properties (velocity, temperature, moisture, pressure) and the particle properties (mass concentration, size distribution, charge/mass ratio). The scrubber operating parameters also will be recorded for each test."

FLUX FORCE/CONDENSATION (FF/C) SCRUBBER PILOT PLANT (APT, INC., 1974 TO 1975)

Following APT's previous theoretical and bench-scale FF/C scrubber studies, it was decided to have them conduct a 5000 to 10,000 cfm pilot demonstration of an FF/C system. APT was to test the pilot scrubber on an industrial source of particulate emissions selected jointly by APT and IERL-RTP. The scope of APT's responsibilities was defined in the IERL-RTP project description:

> "APT shall conduct a literature survey to determine alternative FF/C scrubber designs and shall design the pilot scrubber based upon the alternatives considered. APT shall prepare a test plan to document the performance of the scrubber system on a selected industrial source. The testing will determine the particle collection efficiency of the system over the size range of 0.01 to 10 μm, the overall mass efficiency, the operational reliability, and the economics of the system. From the results of the pilot scale tests, APT will prepare an estimate of the cost of an optimum, full-size FF/C scrubber system."

EVALUATION OF WET SCRUBBERS FOR CONTROL OF PARTICULATE EMISSIONS FROM UTILITY BOILERS (METEOROLOGY RESEARCH, INC., 1974 TO 1975)

Complete evaluations of several existing scrubber systems at coal-fired utility boilers was the objective of this study. In addition to utilities companies' interest in scrubbers as SO_2 cleaners, they require performance and economic data on scrubbers applied to remove fly ash. To fill this need, IERL-RTP contracted with Meteorology Research, Inc. to perform the testing and evaluation of scrubbers at several selected sites. The IERL-RTP project description was:

> "Meteorology Research shall test a wet scrubber system on a coal-fired utility boiler to determine scrubber overall mass efficiency and fractional efficiency, ash composition, etc., and shall collect all performance, system operating, system design and cost data necessary to evaluate the performance and economics of the system."

OPERATION OF EPA-OWNED MOBILE UNITS, AERODYNAMIC TEST CHAMBER, AND PILOT SCRUBBERS (MONSANTO RESEARCH CORPORATION, 1974 TO 1975)

IERL-RTP contracted with Monsanto Research Corporation (MRC) to provide personnel, materials, services, and auxiliary equipment to conduct testing programs with EPA-owned equipment. MRC undertook responsibility for all phases of field testing on industrial sources using this mobile equipment. The scope of work which MRC is to provide was defined by IERL-RTP.

> "MRC will operate the following EPA-owned equipment: Mobile Fabric Filter Unit, Mobile Wet Scrubber Unit, Mobile ESP, Mobile Cyclone Facility, Aerodynamic Test Facility, and SO_2 Model Pilot Scrubber. MRC will provide maintenance for the mobile facilities as well as the associated process equipment and vehicles. MRC will use the Aerodynamic Test Facility to conduct tests on various devices and dusts. MRC will prepare a test plan for each mobile unit."

ROCKET MOTOR EMISSIONS CONTROL (APT, INC. AUGUST TO OCTOBER 1974)

As part of an inter-agency agreement between EPA and the U.S. Air Force, APT, Inc., studied current systems for removing toxic gases and particulate matter from rocket exhausts during ground-based static test firing. The scope of work assigned by IERL-RTP was to:

> ". . . survey the literature and contact installations where high-temperature gas stream control systems are in effect, to gather data and develop mathematical models for fine particulate removal from high-speed, high-temperature gas streams. An analysis of each control system will be made to determine its operating characteristic efficiency, and applicability to the USAF facilities. Variables to be investigated include gas velocity, gas temperature, gas composition, type of fuel used, test-stand geometry, and particle collectability."

ENTRAINMENT CHARACTERISTICS OF MOBILE BED SCRUBBERS
(APT, INC. SEPTEMBER 1974 TO DECEMBER 1974)

The quantity, drop size distribution, and flow pattern of liquid entrainment leaving a scrubber is important information for designing entrainment separators, as pointed out in APT's earlier work. IERL-RTP contracted with them to study experimentally and theoretically the entrainment properties of mobile-bed (turbulent contacting absorber, TCA) scrubbers, TCA support grids without balls, and plate-type scrubbers in power plants. Using the EPA-owned mobile-bed scrubber (developed by APT), APT was to conduct tests in conjunction with selected sources. IERL-RTP defined APT's task as follows:

> "APT shall assemble the pilot scale facility, collect experimental data, and analyze the results. The entrainment is dependent upon the scrubber geometry, gas flow rate, liquid flow rate, suspended solid concentration, and height above the gas/liquid contact zone. The basic pilot plant will consist of a filter, blower, scrubber, observation section, liquid tanks, pumps, etc. APT shall design and construct an entrainment measurement system using techniques developed previously under contract no. 68-02-0637. These techniques involve the use of treated filter papers for droplets over 15 μm in diameter and impactors for sizes below 15 μm."

EVALUATION OF HORIZONTAL SCRUBBER (APT, INC., JANUARY 1975 TO MAY 1975)

A relatively new concept in scrubbing technology is the horizontal spray scrubber. APT, Inc. was assigned the task by IERL-RTP of theoretically and experimentally, on a small scale, studying the collection efficiency of horizontal spray scrubbers. IERL-RTP's task outlined was for APT to:

> "Critically evaluate the available literature from 1969 to the present on horizontal scrubbers.
>
> "Assess the importance of inertial impaction, condensation effects, and Brownian diffusion for particle collection in horizontal scrubbers.

"Develop mathematical models describing particle collection in horizontal scrubbers which include parameters describing the effects of scrubber operating and design factors and important particle collection mechanisms."

EVALUATION OF SYSTEMS FOR CONTROL OF ROCKET MOTOR TEST PAD EMISSIONS (APT, INC., FEBRUARY 1975 TO AUGUST 1975)

Primary emissions from rocket motor test firings needing control are the gases CO, HCl, and HF and Al_2O_3 particulate. The Air Force Rocket Propulsion Laboratory (AFRPL) requested that a study be made of existing scrubbing systems to determine what equipment should be used to clean rocket exhausts at test firing. AFRPL will conduct scrubbing tests on its firing pads according to APT's recommendations. IERL-RTP specified that:

"The contractor will contact the Air Force Rocket Propulsion Laboratory at Edwards AFB, California, for additional information on the emissions from rocket motors. The contractor will design experiments to be conducted by the Air Force Rocket Propulsion Laboratory to obtain data needed to prepare preliminary design of the scrubbing system. The contractor will evaluate the experimental data. The contractor will then relate his findings to the problems of scrubbing the exhaust produced by firing solid fuel rocket motors ranging in thrust from 5,000 pounds to 450,000 pounds. The contractor will pay particular attention to the problems of entrainment separation."

EVALUATION OF ELECTROSTATIC SCRUBBER (APT, INC., APRIL 1975 TO MAY 1975)

Air Pollution Systems, Inc. developed an electrostatic scrubber which IERL-RTP studied briefly via APT, Inc. to determine whether further investigation was merited. The evaluation requested by IERL-RTP had this scope:

"Complete a limited literature search to determine if similar devices have been developed or proposed by others. Determine if the device is truly novel and define the mechanisms which are responsible for particulate capture. Determine the reliability and significance of any experimental data submitted. Assess the practicality of the device for collection of fine particulate. Estimate the capital and operating costs for the device evaluated. Determine which sources might be controlled by the new system and estimate the probability of successful application.

"This evaluation is a paper study only and does not require testing by the contractor.

"A recommendation will be made as to whether the device should be tested by EPA. If the recommendation is to test the device, a recommendation for the testing procedures to be used will be provided."

EFFECTS OF INTERFACIAL PROPERTIES OF FINE-PARTICLE SCRUBBING (METEOROLOGY RESEARCH INSTITUTE, JUNE 1975)

Introduction

In the development of engineering design methods for the evaluation of scrubber systems, mathematical models to date (the Scrubber Handbook,[4] for example) have tended to ignore the effects of particle-liquid interfacial properties. That is, collection efficiency is typically equated with "target" or collision efficiency, tantamount to assuming that all particles contacting a scrubber drop are retained by the drop. The interfacial properties may be such as to inhibit the retention of nonwettable particles, however. There are theoretical results showing that a nonwettable particle may bounce off the drop under certain conditions, such as low impingement velocity.[33] However, experimental investigations have been subject to dispute. (See References 26-31).

In view of the dearth of data and its possible significance for improvement of scrubber design for finer particle collection, IERL-RTP is initiating a program to study this problem. This will supplement the work being done by Southern Research Institute on the growth of hygroscopic aerosols in scrubber environments.

Goals

The scope of work defined by IERL-RTP includes effectively the following:

1. Literature review and evaluation, with identification of weak areas, regarding the nature of particle-liquid interface interactions and how they might affect particle retention in scrubbing. The literature is likely to extend into other fields such as cloud physics and precipitation scavenging.

2. Development of theoretical models of particle retention as functions of particle size and their properties governing the surface interaction.

3. Well-defined experiments to test the theoretical models, using fine, relatively monodisperse aerosol particles.

4. Assessment of the results of the theory and experiments with regard to the relative importance of interfacial effects in scrubbing.

5. Identification of remaining problem areas and the nature of further analysis and measurements to be done.

6. Recommendations for applying the results to enhance the design of scrubbers for particulate pollution control.

MOBILE BED FLUX FORCE/CONDENSATION (FF/C) SCRUBBERS FOR COLLECTION OF FINE PARTICLES (CONTRACT IN NEGOTIATION)

Introduction

Previous contract efforts showed that FF/C scrubbing was a feasible concept. In earlier work, mathematical models and design equations were developed for a sieve plate scrubber and a spray scrubber which make use of diffusiophoresis and particle growth due to water vapor condensation. Significant advantages would accrue if it were possible to combine commonly used mobile bed scrubbers for SO_x with particulate collection by the same device. IERL-RTP is therefore in the process of negotiating a contract for an in-depth study of this project.

Goals

The objectives of the proposed study would be to:

1. Determine feasibility of using mobile bed scrubbers as Flux Force/Condensation Scrubbers.
2. Compare mobile bed FF/C scrubber with the spray and sieve plate FF/C scrubber.

Methods

The recommended approach to achieving the study objectives is:

1. Conduct preliminary tests of collection efficiency with a mobile bed scrubber.
2. Design and construct an entrainment separater for the pilot mobile bed scrubber (gas flow rate $\geq$ 1000 acfm, 0.5 m^3/s).
3. Undertake an experimental study of FF/C scrubbing in mobile bed scrubbers. Parameters of interest are: number of scrubber stages, condensation ratio, liquid-to-gas flow rate ratio, bed height, pressure drop, particle diameter, particle concentration, gas velocity, liquid entrainment. Run tests with no condensation.
4. Use above results to develop mathematical models and design equations. Compare predictions with the reported performance of the mobile-bed TCA Scrubber in EPA's Alkali Scrubbing Test Facility at TVA Shawnee Power Plant.
5. Recommend an FF/C scrubber configuration for pilot demonstration based on critical technical and economic comparison of studied scrubbers.

EFFECTS OF ENERGY CONSUMPTION AND ENERGY SUPPLY MODE ON SCRUBBER OPERATION (STANFORD RESEARCH INSTITUTE, JUNE 1975)

Introduction

Wet scrubbers may have energy supplied to them in a variety of ways. The energy consumption of a scrubber per unit volume of gas treated and whether some of this energy may be taken at no cost from process heat will have great bearing on the economic justification of a given scrubber. Consequently, IERL-RTP has negotiated a contact to study the effect of energy consumption and supply mode on scrubber collection efficiency and economy.

Goals

The goals of the study will be to:

1. Determine effects of energy utilization and the varied means of supplying energy on collection efficiency of wet scrubbers.
2. Recommend a research and development program to achieve scrubbers which make optimum use of energy.

Other objectives to be reached are specified in the IERL-RTP scope of work:

1. "Identify the mechanisms by which the energy supplied is utilized to collect particles.
2. "Identify other energy consuming mechanisms, e.g., friction.
3. "Develop quantitative relationships between the energy supplied to the scrubber and the particle collection efficiency.
4. "Explain any differences in the energy-particle collection efficiency relationships that may exist for different types of scrubbers."

Methods

The study will include a literature survey of the energy consumption and supply problem in scrubbers. A bench scale experimental effort should be made to evaluate the following scrubber types within the above framework:

1. Scrubbers which derive contacting power from the available gas stream.

2. Scrubbers which utilize mechanical rotors.

3. Scrubbers which derive contacting power from a liquid stream.

Controlled, monodisperse, nondeliquescent test aerosols (at least three different sizes below $d_p = 3\ \mu m$) will be employed. The use of series scrubbing will be investigated.

SECTION VI

REFERENCES

1. Mergenthaler, H. and D. Keller. Developments in Wet Scrubbers. Staub (English) 26(6):1-4. June 1966.

2. Particulate Pollutant System Study. Vol. II. Fine Particulate Emissions. Midwest Research Institute. Prepared for U.S. EPA. August 1971.

3. Calvert, S. Engineering Design of Wet Scrubbers. J APCA 24:929-934. 1974.

4. Calvert, S., J. Goldshmid, D. Leith, and D. Mehta. Scrubber Handbook. Vol. I. APT, Inc. Riverside, California. Report Numbers NTIS PB-213016, EPA-R2-72-1182. Environmental Protection Agency. July 1972.

5. Semrau, K. and C. L. Witham. Wet Scrubber Liquid Utilization. Stanford Research Institute. Menlo Park, California. Report Number EPA-650/2-74-108. Environmental Protection Agency. October 1974. 116 p.

6. Fuchs, N. The Mechanics of Aerosols. New York, Pergamon Press. 1964. 408 p.

7. Cooper, D. W. Fine Particle Control by Electrostatic Augmentation of Existing Methods. Paper #75-02.1. Presented at the 68th Annual Meeting of the Air Pollution Control Association. Boston. June 1975.

8. Melcher, J. R. and K. S. Sachar. Charged Droplet Scrubbing of Submicron Particulate. Draft Final Report to EPA for Contract No. 68-02-0250. July 1974.

9. Lear, C. W., W. F. Krieve, and E. Cohen. Charged Droplet Scrubbing for Fine Particle Control. J APCA 25(2):184-189. February 1975.

10. Pilat, M. J. Collection of Aerosol Particles by Electrostatic Droplet Spray Scrubbers. J APCA 25(2):176-178. February 1975.

11. Sparks, L. E. and M. J. Pilat. Effect of Diffusiophoresis on Particle Collection by Wet Scrubbers. Atmos Environ 4:651-660. 1970.

12. Lancaster, B. W. and W. Strauss. A Study of Steam Injection Into Wet Scrubbers. Ind Eng Chem Fundamentals. 10(3):362-369. March 1971.

13. Fuchs, N. and A. Kirsch. The Effect of Condensation of a Vapor on the Grains and of Evaporation From Their Surface on the Deposition of Aerosols in Granular Beds. Chem Eng Sci 20:181-185. 1965.

14. Calvert, S., J. Goldshmid, D. Leith, and N. C. Jhaveri. Feasibility of Flux Force/Condensation Scrubbing for Fine Particulate Collection. APT, Inc. Riverside, California. Report Number EPA-650/2-73-036. Environmental Protection Agency. 1973.

15. Semrau, K. T. and C. L. Witham. Condensation and Evaporation Effects in Particulate Scrubbing. Paper # 75-30.1. Presented at 68th Annual Meeting of the APCA. Boston, Mass. 1975.

16. Schauer, P. J. Removal of Submicron Aerosol Particles From a Moving Gas Stream. Ind Eng Chem 43(7):1532-1538. July 1951.

17. Waldmann, L. and K. H. Schmitt. Thermophoresis and Diffusiophoresis of Aerosols. In: Aerosol Science, Davies, C. N. (ed.). New York, Academic Press, 1966. p. 137-161.

18. Lapple, C. E. and H. J. Kamack. Performance of Wet Dust Scrubbers. Chem Eng Prog. 51(3):110-121. March 1955.

19. Semrau, K. T., C. W. Marynowski, K. E. Lunde, and C. E. Lapple. Influence of Power Input on Efficiency of Dust Scrubber. Ind Eng Chem 50(11):1615-1620. November 1958.

20. Slinn, W. G. N. and J. M. Hales. A Reevaluation of the Role of Thermophoresis as a Mechanism of In- and Below-Cloud Scavenging. J Atmos Sci 28:1465. 1971.

21. Goldsmith, P. and F. G. May. Diffusiophoresis and Thermophoresis in Water Vapor Systems. In: Aerosol Science. Davies, C. N. (ed.). New York, Academic Press. 1966. p. 163-194.

22. Calvert, S. and N. C. Jhaveri. Flux Force/Condensation Scrubbing. J APCA 24(10):947-952. October 1974.

23. Nannen, L. W., R. E. West, and F. Kreith. Removal of SO_2 From Low Sulfur Coal Combustion Gases by Limestone Scrubbing. J APCA 24:29-39. 1974.

24. Calvert, S., I. L. Jashnani, S. Yung, and S. Stalberg. Entrainment Separators for Scrubbers - Initial Report. APT, Inc. Riverside, California. Report No. EPA-650/2-74-119-a. Environmental Protection Agency. October 1974.

25. Statnick, R. M., and D. C. Drehmel. Fine Particle Control Using Sulfur Oxide Scrubbers. J APCA. 25:605-609. June 1975.

26. Berg, T. G. O., T. A. Gaukler, and L. A. Squier. Kinetics of Wetting in Washout of Dust. Aerojet - General Corp., Downey, California. In: Radioactive Fallout From Nuclear Weapons Tests. U. S. Atomic Energy Commission. 1965. 281-300 p.

27. Engelmann, R. J. A Surface Energy Model in the Raindrop Wetting of Scavenged Particles. Abstracted from: Report No. HW 79382. U.S. Atomic Energy Commission. Hanford, Washington. 1963.

28. Rayleigh, Lord. The Influence of Electricity on Colliding Water Drops. Proc Roy Soc 28:406. 1879.

29. Fuchs, N. A., F. I. Murashkevich, and A. D. Raikhin. Preliminary Report on the Efficiency of Collisions Between Dust Particles and Water Droplets. Staub 33(4):182-183. April 1973.

30. Adam, N. K. The Physics and Chemistry of Surfaces. London, Oxford Univ Press. 1930. 402 p.

31. Berg, T. G. O. The Mechanism of Washout. Aerojet - General Corp. Downey, California. Report No. 0780-01(02)SP. 1963. 44 p.

32. McCully, C. R., M. Fisher, G. Langer, J. Rosinski, H. Glaess, and D. Werle. Scavenging Action of Rain on Airborne Particulate Matter. Ind Eng Chem 48:1512-1516. 1956.

33. Pemberton, C. S. Scavenging Action of Rain on Nonwettable Particulate Matter Suspended in the Atmosphere. In: Aerodynamic Capture of Particles, Richardson, E. G. (ed.). London, Pergamon Press. 1960. 200 p.

34. McDonald, J. E. Rain Washout of Partially Wettable Insoluble Particles. J Geophys Res 68(17):4993-5003. September 1963.

35. Rozen, A. M., and V. M. Kostin. Intern Chem Eng 7:464. 1967.

36. Calvert, S., N. C. Jhaveri, and S. Yung. Fine Particle Scrubber Performance Tests. APT, Inc. Riverside, California. Report No. EPA-650/2-74-093. EPA. October 1974.

37. Kotov, N. A. Influence of Spray Entrainment on Gas Scrubber Efficiency. Translated by EPA from Vodosnabzheniye: Sanitaria Tekhnika. 7:31-34. 1972.

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15. SUPPLEMENTARY NOTES

16. ABSTRACT The report gives: an introduction to fine particle control scrubber programs supported by EPA's Industrial Environmental Research Laboratory at Research Triangle Park in North Carolina (IERL-RTP); and topical and chronological overviews of the various projects which IERL-RTP has sponsored relating to scrubber technology. Having reviewed the state-of-the-art which culminated in the Scrubber Handbook, IERL-RTP sponsored scrubber tests which generally validated the models presented in the Handbook. Possible exceptions (mobile-bed scrubbers and series scrubbing with low-energy devices) became objects of further study. Two major mechanisms for increasing scrubber efficiency have been studied by IERL-RTP contractors: flux-force/condensation scrubbing (use of diffusiophoresis and condensation growth of particles), and electrostatic augmentation (scrubbing with charged droplets); both have shown efficiencies which are higher than those achieved by conventional means at equal power consumption levels. Problems with entrained water droplets have caused IERL-RTP to fund theoretical and experimental research in entrainment separator technology, some of the results of which are presented. The hypothesis that particle wettability is important in determining scrubbing efficiency is to be tested by an IERL-RTP sponsored research program.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
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