ABSTRACT

Title of Thesis: Surfactant Enhanced Scrubbing in an
Ejector Venturi Scrubber of Sulfur
Dioxide from Air Exhaust Streams.
Humberto Roman, Master of Science, 1981.
Thesis Directed by: Professor Richard B. Trattner.

The objective of this work was to determine the feasibility of applying the Surfactant Enhanced Scrubbing technique to the removal of sulfur dioxide using an ejector venturi scrubber.

Surfactants were chosen according to information from manufacturers. Those surfactants which offered good behavior in the presence of acidic solutions (low pH), and anti-corrosion characteristics were tested.

In the first phase, experiments were performed to determine the behavior of the foams in the ejector venturi scrubber. A foam destruction system was used when foaming conditions required it. In the second phase dynamic runs were performed to determine the removal efficiencies for each surfactant at various concentrations.

These studies determined that the application of Surfactant Enhanced Scrubbing technique in the ejector venturi scrubber is very practical and promising. Further research should be done to improve this technique.

SURFACTANT ENHANCED SCRUBBING
IN AN EJECTOR VENTURI SCRUBBER OF
SULFUR DIOXIDE FROM AIR EXHAUST STREAMS

by

Humberto Roman

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New Jersey Institute of Technology in partial fulfillment of
the requirements for the degree of
Master of Science in Environmental Engineering

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APPROVAL SHEET

Title of the Thesis: Surfactant Enhanced Scrubbing in an Ejector Venturi Scrubber of Sulfur Dioxide from Air Exhaust Streams.

Name of Candidate: Humberto Roman.
Master of Science in Environmental Engineering, 1981.

Thesis and Abstract Approved:

Richard B. Trattner
Professor of Chemistry
Chairman, Environmental Engineering.

Date Approved: April 27, 1981.

VITA

Name: Humberto Roman

Permanent address:

Degree and date to be conferred: M. Sc. Environmental Engineering, May 28 1981

Date of birth:

Place of birth:

Secondary education: Colegio Bolivariano, Caicedonia Valle, Colombia.

Collegiate institutions attended:	Dates	Degree	Date of Degree
Universidad del Valle, Cali Colombia.	1966-1973	B. S. Sanitary Engineering.	1973
New Jersey Institute of Technology, Newark, N.J.	1977-1981	M. Sc. En.E.	1981

Major: Environmental Engineering.

To my mother, my brother and his wife.

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INTRODUCTION

Legislation on Sulfur Dioxide Control

Control of pollutants has been, for the past 15 years, an important issue in the United States' environmental legislative program. Application of technological and engineering solutions to the control of pollution has increasingly been called to public attention. As a result, the public perceives that pollution at any level is responsible for health and welfare effects. This is a difficult situation that has to be relieved by means of sound and practical technology. A brief summany concerning sulfur dioxide control and existing legislation is presented here:

The Clean Air Act of 1964 and its subsequent amendments of 1967, 1970, and 1977 represent one part of these initiatives.

According to the Clean Air Act Amendments of 1970, certain air pollutants should be controlled primarily by two mechanisms: (1) National Ambient Air Quality Standards (NAAQS), which were established for the explicit purpose of protecting public health and welfare; and (2) emission standards for new sources, or New Source Performance Standards (NSPS). In addition, the 1970 Amendments required that each state develop a plan to provide for implementation, maintenance and enforcement of the NAAQS.

The establishment of technology-based NSPS reflects a technology-forcing principle. This means that as more effective emission control technqiues are demonstrated, the NSPS are revised to reflect the performance capabilities of the improved technologies. These revised NSPS, in effect, force new stationary sources to apply the improved technologies. The 1977 Amendments have reaffirmed and strengthened this concept of technology-based NSPS.

Some revisions of the 1977 Amendments either reinforce or develop concepts related to:

1. new source performance standards;
2. air quality requirements for the Prevention of Significant Deterioration (PSD), which apply to sources in areas where

the NAAQS are currently being achieved for a given criteria pollutant;

3. Requirements for nonattainment areas, which apply to sources in areas where the NAAQS are not being achieved for one or more criteria pollutants.

Prevention of significant deterioration areas are those where the ambient air quality is currently better than the NAAQS. Under the 1977 Amendments, PSD areas are designated as Class I, Class II, or Class III, depending upon the degree of future air quality deterioration that is to be allowed. Table 1 shows the air quality increments (increases over the background concentrations of certain air pollutants) which are allowed for each classification. The NAAQS are also shown for comparison. In the 1977 Amendments, Congress established allowable air quality increments for both sulfur dioxide and particulate matter and directed Environmental Protection Agency (EPA) to establish increments for the four remaining criteria pollutants by mid 1979. Initially, all PSD areas are designated Class II, except all pre-existing international parks, national wilderness areas and national memorial parks which exceed 6,000 acres. These are designated Class I. Provisions also exist for changing the classification of certain areas, except for Class I areas described above which cannot be redesignated.

Table 1

Comparison of NAAQS and PSD Increments for Sulfur Dioxide

Units $\mu g/m^3$)

Pollutant	Averaging Time	NAAQS		PSD Increments		
		Primary[1]	Secondary[2]	Class I	Class II	Class III
Sulfur Dioxide	Annual	80	--	2	20	40
	24 hr[3]	365	--	5	91	182
	3 hr[3]	--	1300	25	512	700

1. Primary standards were established to protect public health.
2. Secondary standards were established to protect welfare.
3. Not to be exceeded more than once a year.

Provisions for PSD have been interpreted by EPA as an additional ambient air quality standard which is more restrictive than the NAAQS.[1] However, with respect to sulfur dioxide, there is a substantial body of evidence which indicates that the current NAAQS provide an adequate margin of safety for the protection of public health and welfare. A critical review on sulfur dioxide and health effects was published in the Journal of Air Pollution Control Association in May 1978.[2]

The NSPS for sulfur dioxide, established by EPA pursuant to the 1970 Amendments, is 1.2 pounds of sulfur dioxide per million Btu. of heat input to the boiler. For coal possessing a sulfur content of 3% by weight and a heating value of 11,000 Btu. per pound, this standard is equivalent to a 78% reduction in sulfur dioxide emissions from the untreated fuel. For a 1% sulfur coal of the same heating value, only a 34% reduction is required to comply with the same emission standard.

The requirement that new fossil fuel - fired elective generating stations incorporate technological control systems eliminates low sulfur coal as the sole means of complying with the sulfur dioxide control requirements of the 1977 Amendments. As a result, two methods of compliance are available to electric utilities: (1) removing sulfur dioxide from the combustion (flue) gases after burning the coal and/or (2) cleaning the coal prior to or during combustion (e.g., solvent refining of coal, coal gasification, and fluidized-bed combustion).

Of these two compliance alternatives, systems for removing sulfur dioxide from flue gases are more highly developed. Effective coal-cleaning systems, capable of achieving the required levels of removal, are still at least five years from commercialization.

Sulfur Dioxide (SO_2)

Descriptions:

Sulfur dioxide is a highly irritant, non-flammable, colorless and poisonous gas with a sharp odor (maximum safe concentration 5 ppm). It is a little more than twice as heavy as air. It condenses to a clear liquid which yields white crystals on further cooling. SO_2 is thermodynamically stable.

Sulfur dioxide is one of the very minor and variable constituents of the atmosphere. Volcanic and other terrigenous gases contain on the order of 10% sulfur-containing gases, largely sulfur dioxide and hydrogen sulfide. In some areas the amount of sulfur dioxide in the atmosphere is increasing and reaches measurable concentrations as the result of heavy and widespread industrial activity.[3]

Uses:

Some of the uses of sulfur dioxide are as follows: as a preservative for beer, wine and meats; in the manufacture of sulfites and hydrogen sulfites; in solvent extraction of lubricating oils; as a general bleaching agent of oils and foods; in sulfite pulp manufacture; in the cellulose and paper industries; as a refrigerant in the ice industry; in disinfecting; in tanning.

Toxicity:

Gaseous sulfur dioxide is highly irritating and is practically irrespirable. It is readily detectable in concentrations of 3-5 ppm and thus provides ample warning of its presence. In higher concentrations, the severely irritating effect of the gas makes it unlikely that any person would be able to remain in such a contaminated atmosphere unless he were unconcious or trapped.

Liquid sulfur dioxide may cause skin and eye burns upon contact with these tissues which result from the freezing effect on the liquid on the skin or eyes.

Acute exposure to sulfur dioxide has the following effects: 8-12 ppm.

causes throat irritation, coughing, constriction of the chest, tearing and smarting of the eyes; 150 ppm. causes extreme irritation and can be tolerated only for a few minutes; 500 ppm. is so acutely irritating that it causes a sense of suffocation. No systemic effects are known of acute exposure to sulfur dioxide.

Sulfur dioxide damages human white blood cells in tissue culture. When 5.7 ppm. sulfur dioxide by volume in air is bubbled through cultures of lymphocytes, it causes fewer of the cells to synthesize DNA, divide, or grow. The cells are smaller than those grown in SO_2-free air, and about 20% of the cells have altered chromosome structures. It has also been found that animals exposed to sulfur dioxide become less resistant to microorganisms.

Properties of sulfur dioxide

Table 2 shows some physical properties of sulfur dioxide.

Table 2

Physical Properties of Sulfur Dioxide

Molecular weight	64.063
Vapor pressure (70°F)	34.4 psig.
Specific volume (70°F, 1 atm)	5.9 ft^3/lb
Boiling point (1 atm)	14.0°F (-10.0°C)
Melting point (1 atm)	-103.9°F (-75.48°C)
Latent heat of vaporization (b·p)[a]	92.8 cal./g.
Latent heat of fusion (m·p)[b]	27.6 cal./g.
Specific heat, liquid (0°C)	0.318 cal./(g)(°C)
Specific heat, gas (25°C, 1 atm)	
C_p	0.1488 cal/(g)(°C)
C_v	0.1154 cal/(g)(°C)
Critical temperature	315.5°F (157.5°C)
Critical pressure	1143.6 psia (77.8 atm.)
Critical density	0.524 g/ml

Table 2 (Continued)

Density, gas (0°C, 1 atm)	2.93 g/ml
Density, liquid (-10°C)	1.46 g/ml
Viscosity, gas (18°C, 1 atm)	124.2 micropoises.
Solubility in water (0°C, 1 atm)	18.59% (by weight)
(20°C, 1 atm)	10.14% (by weight)

a - boiling point

b - melting point

Liquid sulfur dioxide expands about 10% in volume when temperature goes from 20 to 60°C. The pure liquid is a poor conductor of electricity; however, solutions of some salts that are soluble in sulfur dioxide exhibit high conductivity. In liquid state, sulfur dioxide is only slightly miscible with water, is a nonsolvent for sulfur, and is miscible in all proportions with sulfur monochloride.

There is not appreciable decomposition of sulfur dioxide when it is heated to about 2000°C. It does not form flammable or explosive mixtures with air. Sulfur dioxide is readily formed by the air oxidation of sulfur and many sulfides, by the pyrolisis in air of sulfites and thiosulfates, by the reduction of sulfur trioxide and sulfuric acid by metals, carbon, sulfur, and sulfides with heating and by the decomposition of sulfite and bisulfite solutions with strong acids.[4]

Absorption of sulfur dioxide in water

Absorption mechanisms for sulfur dioxide in water have been studied for many years. Lewis and Whitman[5] reported that in the absorption of a very slightly soluble gas from air by water or in the absorption of a pure gas in water, the rate of absorption is controlled by the resistance of a film of liquid at the liquid-gas interface. On the other hand, where a very soluble gas is being absorbed from air by water, the resistance of the gas film at this interface controls.

The over-all resistance to the absorption of sulfur dioxide comprises both gas and liquid film resistances, although the latter is generally of major importance. Resistance to its absorption may be reduced by increasing liquor velocity, temperature and gas velocity, the magnitude of the effect being in the order named. Over-all resistance (R_L) is inversely proportional to the 0.89 power of liquor velocity. The effect of temperature on over-all resistance at low gas and liquor velocities is similar to its effect in a wetted-wall tower; at high liquor velocity, the effect is much greater. Gas velocity affects the resistance to absorption at higher liquor velocity, but is unimportant at low-liquor velocity.

Surfactants: Efficiency, Effectiveness and Foaming Characteristics

The word surfactant stands for surface-active agent, a substance that when present in a system, even at low concentration, adsorbs onto the surfaces or interfaces of the system and alters to a marked degree the surface or interfacial energies of those surfaces (or interfaces). Interface is the boundary between any two immiscible phases; surface denotes an interface where one phase is a gas, usually air.

Two structural groups are present in surface-active agents: the lyophobic group that has very little attraction for the solvent and the lyophilic group that has strong attraction for the solvent. This amphipathic structure of the surfactant has two effects on solutions: (1) concentration of the surfactant at the surface and reduction of the surface tension of the solvent; and (2) orientation of the molecule at the surface with its hydrophilic group in the aqueous phase and its hydrophobic group orientated away from it. For a substance to exhibit surface activity in a particular system, the surfactant molecule must have a chemical structure that is amphipathic in that solvent under the conditions of use.

Two important parameters serve to study the performance of surfactants in interfacial phenomena: (1) efficiency, which is the amount of surfactant required to produce a given amount of change in the phenomenon under investigation; and (2) effectiveness, which is the maximum change in the phenomenon that the surfactant can produce.[6]

Formation of foam is due to air or some other gas entering beneath the surface of a liquid. Expansion of the liquid allows to enclose the air or gas between thin films of liquid. As a result of this phenomenon, a honeycomb-like structure is formed with approximately plane parallel sides. These two-sided films are called the lamellae of the foam. The point where three or more gas bubbles meet is called the plateau border or Gibbs triangles.

No foam occurs in absolutely pure liquids. Similar types of materials, when mixed, do not foam in appreciable amounts. Bubbles of gas entering beneath the surface of a liquid either rupture after contacting each other or escape from the liquid as fast as the liquid can drain away from them.

A lot of research has been made in film stability. The most important contribution is due to Gibbs.[7] According to Gibbs' theories, although thick films will persist for long periods, their existence depends on two factors: (i) a drainage factor; (ii) a film strength factor. Normally the film will drain and eventually rupture when thin.

Gibbs regarded film stability as an equilibrium condition and showed that the surface tension under film deformation must always change in such a way as to resist the deforming forces.

Viscosity of the liquid affects drainage; and in general, the viscosities of the liquid in the films and in the bulk will be identical. However, orientated monolayers on the surface might influence the underlying liquid.

Another factor that influences drainage is bubble size. The capillary suction effect is a major cause of drainage; and, as this effect is proportional to the curvature of the bubble, it is obvious that the drainage rate will depend on bubble size distribution. Thus, it is difficult to compare results of experiments in which the size of bubbles is unknown.

One of the most important factors in determining the probability of film rupture is the recovery power of the film, i.e., its power to resist changes in area. This point is contained in Gibbs' concept of elasticity, and it is bound up with the existence of surface tension gradients in the film.

The mechanical properties of the surface layers also influence film rupture; it is, for example, reasonable to suppose that susceptibility to rupture will be less in a viscous than in a tenuous surface film. Many years ago, Hardy,[8] in a study of the collapse of air bubbles beneath monolayers of oleic acid at various surface pressures, showed that maximum stability was obtained for a certain surface pressure of the monolayer.

This was interpreted to mean that, for maximum stability, the layer at the surface of the bubbles should have the necessary cohesion to withstand shock; and it suggested that the mechanical properties of surface layers might be involved in foam stability.

Brawn et al.[9] have concluded that although high surface viscosity may be desirable, it is not essential for good foam stability.

Foam elasticity is perhaps the most important concept which has emerged so far. The surface tension gradients in elements of the film will restore distortions resulting from drainage and thermal or mechanical shocks as explained by Gibbs.

Burcik[10] considers that the important factors in foam stability are: (i) low equilibrium surface tension, (ii) moderate rate of attainment of surface tension, and (iii) high surface and bulk viscosity.

The mechanical deformation of a film involves stretching, which increases the area per molecule in the surface. This will cause a local increase in surface tension and will create surface flow towards the stretch film; the substrate accompanying the flow of the surface layer will tend to restore the stretched portion of the film to its former thickness.

Fundamentals of Gas Control Mechanisms

Control mechanisms are chemical engineering unit operations which relate to the physical changes that take place. Fluid flow, heat and mass transfer, condensation, absorption and adsorption are included in these unit operations. In addition, some chemical reactions may occur at the same time and must be treated as unit operations.

Diffusion

Diffusion in liquids has been the subject of many investigations. Diffusion coefficients can be calculated from several expressions; however, discrepancies are still in this field. No one equation at this time predicts diffusivities for all systems involving a liquid solvent.[11,12]

The Stokes-Einstein equation[13] was developed in 1905.

$$D_{AB} = \frac{kT}{6\pi \mu_B R_A} \qquad (1)$$

where: D_{AB} = diffusion coefficient of A in B, cm^2/sec;

K = Boltzmann's constant;

T = absolute temperature, $^\circ K$;

μ_B = viscosity of solvent B, cp.;

R_A = radius of the solute A particle.

A hydrodynamic approach was used in this study, and Stokes' law for drag on a spherical particle was employed as the retarding force.

Wilke and Chang[14] based on the same approach came up with the expression:

$$D_{AB} = \frac{7.4 \times 10^{-8} \, (\phi M_B)^{\frac{1}{2}} \, T}{\mu_B \, V_A^{\,0.6}} \qquad (2)$$

where: μ_B = molecular weight of solvent B;

V_A = molar volume of solute A;

ϕ = association member of the solvent which is 2.6 for water, 1.9 for methanol, 1.5 for ethanol, and 1.0 for unassociated substances;

μ_B = solution viscosity, cp.;

D_{AB}, T, as defined before.

This equation was tested for 251 pairs of systems and was found to be accurate within ±10%. The main limitation is the association number (ϕ), which had to be calculated experimentally for associated systems.

Othmer and Thakar[15] observed that log D_{AB} is a linear function of log μ_B. The equation was:

$$D_{AB} = \frac{1.4 \times 10^{-4}}{V_A^{0.6} \; \mu_B \; \mu_W^{c}} \tag{3}$$

where: μ_W = viscosity of water at the temperature of interest, cp.

c = exponential factor ($c = 1.1 \, (\Delta H_{vap\ B} / \Delta H_{vap\ W})$)

$\Delta H_{vap\ B}$ = enthalpy of vaporization of the solvent B, cal./g.mol.

$\Delta H_{vap\ W}$ = enthalpy of vaporization of water, cal./g.mol.

D_{AB}, T, V_A, μ_B, as defined before.

Eyring and co-workers,[16,17] Gainer and Metzner[18] and recently Akgerman[19] developed some studies for predicting gas-liquid diffusivities.

Molecular diffusion is concerned with the movement of individual molecules through a substance by virtue of their thermal energy. Molecular diffusion is the mechanism of mass transfer in fluids moving in laminar flow, although it is always present even in highly developed turbulent flow. The terms diffusion and mass transfer seem to be used more or less interchangeably. The tendency seems to be to use mass transfer as the general term embracing all mechanisms of transport of a chemical species and to reserve diffusion for mass transport by molecular motion within a single phase.

Mass transfer

In order to remove a gaseous pollutant from the carrier gas (usually air) it is necessary to transfer a mass of pollutant from the gas phase to another phase. The other phase is usually a liquid, as in absorption, but may also be a solid, as in adsorption.

There are several mechanisms by which mass transfer can occur: (1) ordinary diffusion, which results from a gradient in the concentration; (2) thermal diffusion, which results from a gradient in the temperature; (3) pressure diffusion, which results from a gradient in the hydrostatic pressure; (4) forced diffusion, which results from different external forces acting upon the different species present; (5) mass transfer by forced convection, which results from the over-all motion of the fluid, this motion being produced by the expenditure of energy upon the fluid; (6) mass transfer by free convection, which results from the over-all motion of the fluid, the motion being produced by inequalities in the density of the fluid; (7) turbulent mass transfer, which results from the motion of eddies through the fluid; and (8) interphase mass transfer, which results from a nonequilibrium situation at an interface.[20]

In mass transfer, gas molecules must be transferred through a boundary region which can be considered as two "films." One film each for the liquid and for the gas phase. These films represent the resistance to the passage of molecules which may be passing through the film in either direction. At steady-state conditions the number of molecules moving in each direction is constant but not necessarily equal. At equilibrium, the number of molecules moving in each direction is equal. The net transfer rate is influenced by the driving forces of temperature, pressure, concentration and affinity of the solvent for the gas molecules (solubility).

Eddy and molecular diffusion affect concentration of molecules on the gas side. Normally, eddy diffusion is created to maintain a uniform concentration of molecules in the bulk of the gas phase. Molecular gaseous diffusion provides the means by which the gas molecules move to the film. A constant concentration in the bulk of the liquid is obtained by means of eddy diffusion, thus moving molecules to and from the film.

Molecules passing through the film and into the liquid can either react chemically or be removed physically to keep them passing back through the film, increasing the net rate of transfer from the gas to the liquid.

The reciprocal of the sum of the reciprocal of the individual resistances is the net overall resistance. Usually one of the films presents a larger resistance, so the total resistance is attributed to the film with the largest resistance. Based on this assumption, "liquid-phase controlling" is said to occur when molecules can pass rapidly through the gas side of the film, and "gas-phase controlling" occurs when most of the resistance is in the gas film. Experience has shown that molecules pass more rapidly through gas films, so "gas-phase controlling" absorptions are more effective for pollutant removal.

The rate at which mass is transferred from one phase to another is proportional to the area and the driving force. The proportionality constant is called the mass transfer coefficient (rate constant). Separate equations can be written for each film. The equation for the gas film is:

$$N_A = k_G \; A \; (p_{AG} - p_{Ai}) \tag{4}$$

The equation for the liquid film is:

$$N_A = k_L \; a \; (c_{Ai} - c_{AL}) \tag{5}$$

where: k_G = gas film mass transfer coefficient, g mole/(hr cm^2 atm);
k_L = liquid film mass transfer coefficient, g mole/(hr cm^2 g mole/cm^3);
N_A = rate of transfer of A through the film, g mole/hr;
A = surface area of mass transfer, cm^2;
p_{AG} = partial pressure of A in gas phase, atm;
p_{Ai} = partial pressure of A at vapor-liquid interface, atm;
c_{Ai} = concentration of A at vapor-liquid interface, g mole/cm^3;
c_{AL} = concentration of A in liquid phase, g mole/cm^3.

The difference in partial pressures and the difference in concentrations in equations (4) and (5) is the driving force for mass transfer. The rate of transfer of molecules of A from the gas phase to the liquid phase must be the same through both films even though one film is controlling because there is no accumulation of molecules between the films.[21]

Gas absorption

Physical and chemical absorption occur when the material taken up is distributed through the entire absorbent (liquid) phase.

Gas absorption phenomena takes place when molecules diffuse to the gas film, pass through both the gas and the liquid films and finally diffuse into the liquid. As it was stated before, the net transfer of molecules through each film is the same. Equations (4) and (5) can be set equal to each other.

$$N_A = k_G\ A\ (p_{AG} - p_{Ai}) = k_L\ A\ (c_{Ai} - c_{AL}) \qquad (6)$$

Overall mass transfer coefficients are used with pressure and concentration values that reflect the overall or complete gradient across both films. The overall mass transfer equations using overall absorption coefficients can be written for each film. Combining these in the same manner as equation (6),

$$N_A = K_G\ A\ (p_{AG} - p_{AL}) = K_{LA}\ (c_{AG} - c_{AL}) \qquad (7)$$

where: N_A = rate of absorption of A, g mole/hr;

A = surface area for absorption, cm^2;

K_G = overall gas absorption coefficient, g mole/(hr cm^2 atm);

K_L = overall liquid absorption coefficient, g mole/(hr cm^2 g mole/cm^3);

p_{AL} = partial pressure of A if it were in equilibrium with a liquid solution having that concentration of A, atm.

The p_{AL} and c_{AG} terms are pseudo-quantities. The first term is not a partial pressure of A in the liquid; however, it refers to a vapor condition that could exist above the liquid. No defining statement is made for c_{AG} which could be thought of as being the concentration of A in the gas in units of g mole/cm^3.

Factors affecting gas-liquid mass transfer rates

Following are several factors which affect mass transfer in gas-liquid dispersions:[22]

1. Physical and chemical properties of gas and liquid.
2. Type of gas distributor, orifice diameter, spacing, and position.
3. Dimensions of column or tank, baffles (number, position, size).
4. Type of mechanical agitator, size and relative dimensions.
5. Velocity of rotating impeller and energy input.
6. Gas flow rate.
7. Continuous phase flow rate in countercurrent flow system.
8. Presence of chemical reaction, concentration of electrolytes.
9. Position of downcomers in multiple countercurrent systems.
10. Presence of solid catalysts.
11. Gas-liquid ratio (G/L) in both cocurrent and countercurrent systems.
12. Residence time.

For a given system, the dependent parameters are:

1. Bubble size;
2. Gas holdup;
3. Bubble velocity of rise or relative slip velocity;
4. Actual power input.

The interrelations of all these factors make a single general correlation impossible to achieve. However, some attempts have been made and several reports have been published which individually correlate some of these factors for various types of systems within a certain range of physical properties and experimental variables.

Yoshida, F., Akita, K.[23] have shown that the liquid phase mass transfer coefficient (k_L) may be assumed to be practically independent of the operating conditions -- i.e., column height, gas flow rate, bubble diameter, and mixing intensity. This simplification allows one to assume that for all practical purposes the volumetric transfer coefficient, k_{LA}, depends only on the variation of the specific area with the operating conditions.

Van Koevelen,[24] Quigley, Johnson and Harris,[25] Eckeufelder,[26] Shulman and Molstad,[27] and Calderbank,[28] among others, did a large amount of research on bubble size correlations. Reports on this matter show that the average bubble size increases with gas holdup owing to coalescence of the smaller bubbles. The ultimate bubble size in the gas-liquid contactor, however, depends primarily on the turbulence in the continuous phase. Bubble size decreases in the presence of electrolytes in solutions and/or increased agitation. The relationship between bubble size and agitation seems to depend on which mixing regime is controlling -- viscous shear regime, kinetic energy regime, or coalescence prevention regime.

Relationships for overall volumetric mass transfer coefficients have been reported by Hanhart, J.,[29] Westerterp, K.R.,[30] Hixson and Gaden[31] and others. Differences between several reported studies concerning overall mass transfer coefficients are due to the following factors: geometry of the systems, range of operating conditions, definition of concentration driving force (including effects of surface abrasion at high mixing intensity), initial bubble size (especially important at low gas flow rates and low agitation -- at high superficial gas velocities, coalescence takes place and k_{LA} ceases to be a function of initial bubble size.

Sulfur Dioxide Removal Technology

Currently, as many as 60 methods for removing sulfur dioxide from flue stack gas are known to be effective with efficiencies ranging from 90% to 96% and some of them with up to 98% and 99.5% efficiencies.

Gas purification processes in air pollution control technology have been based mainly on elimination of SO_2 from stack gases.

Operating expenses of considerable magnitude are incurred by the time gases of the type of SO_2 are cleaned, cooled for processing and forced through an SO_2 recovery system and design. Since process economies for SO_2 removal processes are seldom attractive, the primary incentive for its recovery must be air pollution abatement.[32]

Water scrubbing was the first method, historically reported, for removing SO_2 from flue gas to absorb SO_2 into solution. Two large power plants in England (1932) used this method. Costs and operating difficulties have discouraged additional commercial installations of water scrubbing systems.[33]

Following, some of the earlier methods for SO_2 removal:[34]

Sulfidine Process: This process uses as an absorbent a mixture of xylidine and water (approximately 1:1 by weight). Contact takes place in a packed absorber, where the xylidine reacts with SO_2 to form xylidine sulfite. The liquid absorbent is stripped of SO_2 by heating. Flue gases are cleaned in Cottrell (electrostatic) precipitators prior to processing. Vapors from the stripping column are cooled and then scrubbed in a water wash column to reduce the xylidine content to a very low level. Essentially pure SO_2 is produced from the water wash column.

Asarco Process: This process represents an improvement on the Sulfidine Process with regard to reagent loss, steam consumption, and labor requirements. The absorbent used may be either dimethylaniline (DMA) or xylidine. However, DMA has been used in all commercial installations. The Asarco Process uses a water wash to scrub absorbent from the overhead gas from the stripper after the gas is cooled. The SO_2 stream is then dried by a countercurrent wash of 98 wt % H_2SO_4. Compression, cooling, and condensation of the SO_2 stream then follow to yield a liquid SO_2 product. At SO_2 concentrations below 3.5 mole % in the flue gas, xylidine has a competitive advantage over DMA as an absorbent.

Cominco Process: This process is based on absorption of SO_2 in an aqueous solution of $(NH_4)_2SO_3$. The absorbed SO_2 is liberated by addition of H_2SO_4 to the solution, forming $(NH_4)_2SO_4$ as a by-product. An impure SO_2 stream, containing some air, is produced from the top of the stripper. This stream is usually sent to a sulfuric acid plant. Ammonia is continuously added to the absorber, and H_2SO_4 and air are added to the stripper. A 40 wt % $(NH_4)_2SO_4$ solution is produced from the bottom of the stripper.

Fulham-Simon-Carves Process: In this process SO_2 is absorbed in a solution of ammonia and water, and the resulting liquid is subjected to high temperature (360°F) and pressure (200 psig) conditions in an autoclave. Autooxidation of the SO_2 occurs with the formation of $(NH_4)_2SO_4$ and sulfur. These by-products are separated and sold as separate products. Because some of the SO_2 is converted to sulfur, the NH_3 consumption is not as high as in the Cominco Process.

The principal advantage of this process over most SO_2 absorption processes is that the oxidation of SO_2 to form sulfates, which invariably occurs, is not deleterious, since $(NH_4)_2SO_4$ is the primary product.

Battersea Process: This process uses a very dilute aqueous solution of alkaline salts to remove SO_2 by absorption and subsequent oxidation. This process was one of the very first to be used commercially for SO_2 removal from power plant stack gases. An oxidation catalyst (crude $MnSO_4$) was added to the solution from the bottom of the absorber. Oxidation is derived at this point to make the waste water more suitable for river disposal.

Cyclic Lime Process: In this process, flue gas is contacted with a slurry of $CaSO_4$ in water. To keep the solution alkaline, lime or chalk is added continuously and reacts with the SO_2 as it is absorbed. The SO_2 is absorbed in an aqueous solution containing $Ca(OH)_2$ (or $CaCO_3$). Calcium sulfite is formed first and then oxidized rapidly to $CaSO_4$, when in solution, by oxygen absorbed from the flue gas. Both $CaSO_3$ and $CaSO_4$ are sparingly soluble in water; consequently, these materials precipitate to form a sludge which becomes a waste product. This process, therefore, does not produce a salable by-product.

Zinc Oxide Process: This process requires flue contact with a solution of Na_2SO_3 and $NaHSO_3$. The absorption of SO_2 causes an increase in the bisulfite content. The solution leaves the absorber and passes to a clarifier where particulate matter is separated, and finally to a mixer where it is treated with ZnO. At this point, the original ratio of sulfite to bisulfite is restored. A precipitate of $ZnSO_3$ is formed. The solution is agitated to promote crystal growth. Then the $ZnSO_3$ precipitate is removed by settling and filtration, and the filter cake is dried and calcined. Calcination of $ZnSO_3$ produces a gas consisting of 30% SO_2 and 70% water vapor. The gas is cooled, dried, and compressed to produce a virtually pure liquid SO_2 product. Zinc oxide from the calciner is recycled back to the process.

Basic $Al_2(SO_4)_3$ Process: This process is based upon absorption of SO_2 in a solution of aluminum hydroxide-sulfate and regeneration of the absorbent by heating. The absorbent solution is prepared by treating $(NH_4)_2SO_4$ solution with limestone in a mixer and separating the gypsum precipitate. Three or four absorption towers are used to reduce the SO_2 content from, say, 5 to 0.2 mole % or possibly lower. The solution passes through the series of towers in a countercurrent direction to the gas, with cooling between stages to remove heat of absorption. A stripper vessel equipped with reboilers is used to regenerate the solution by heating. The SO_2 is revolved, cooled and dried to produce a nearly pure product of SO_2 gas. The stripped solution is passed through heat exchangers and recycled back to the absorber.

Phosphoric acid is added in the process to inhibit crystallization of $Al_2O_3 \cdot 3SO_2 \cdot 3 \cdot 5 \cdot H_2O$. Also, methylene blue is added to inhibit oxidation of SO_2 to sulfate.

More Recent Methods of Removing SO_2

The methods of removing SO_2 may be categorized into four broad groups:

A. Dry Absorption Processes,
B. Wet Absorption Process,
C. Catalytic Oxidation Processes,
D. Wet and Dry Adsorption Processes.

The wet absorption processes appear to be the most popular; however, processes in each category are available commercially. A brief discussion will follow.

A. Dry Absorption Processes.

1. Limestone or Dolomite Injection.

This is a very simple method that requires the injection of pulverized limestone or dolomite directly into the furnace. H.L. Falkenberry[35] reports that the dry limestone injection process cannot be expected to remove more than about one half of the sulfur oxides, even if twice the stoichiometric quantity of limestone is used.

The process is quite attractive because it has a low capital cost; it can be applied to either coal-burning or oil-burning power plant boilers; it is simple to design and install; and it is simple to operate. However, a low limestone utilization rate of 25 - 35% is a serious disadvantage. This process is said to remove 70% of the SO_2 from the flue gas.

2. U.S. Bureau of Mines Alkalized-Alumina Process.

This process uses alkalized alumina (Na_2O, Al_2O_3) to remove SO_2 from the flue gas. In this process, oxides of sulfur are removed by adsorption on the hot solid adsorbent. The SO_2 is oxidized and subsequently reacts with the metal oxide to form the sulfate.[36]

Based on a study made for an 800-MW coal-burning power plant, the Alkalized-Alumina Process shows the lowest capital investment and the lowest operating cost when compared with the German Reinluft Process and the Monsanto Cat-Ox Process.

Some advantages of the Alkalized-Alumina Process are:

a. No cooling of the flue gas before processing, which increases the process heat recovery efficiency;

b. Low pressure drop of the adsorbent contacting method, which is flexible in its range of gas velocities and adsorbent particle size;

c. Carbon steel construction of the contacting vessel, which is quite inexpensive because it has no internal baffles or other fixtures;

d. A lower capital investment and operating cost than most of the competitive commercially proven processes;

e. Production of elemental sulfur, a more readily marketable product, rather than sulfuric acid or ammonium sulfate.

Some disadvantages of the process are:

a. The difficulty of applying the process to existing plants (the units must be installed between the economizer and air preheater); this usually limits its application to new power plant installations;

b. The susceptibility of the adsorbent to attrition and to clogging by accumulation of adsorbent "dust;" one source[37] reports actual attrition losses of about 7%, whereas process economics demand a loss of about 0.1%.[38]

3. Mitsubishi Manganese Dioxide (DAP-Mn) Process.

This is one of the most advanced dry adsorption processes. This process was developed by Mitsubishi Heavy Industries, Ltd., of Tokyo, Japan. Mitsubishi has found efficiencies in the range from 90 to 98% removal of SO_2. In industry, however, a removal efficiency of 90 - 95% is usually adequate.

The DAP-Mn Process uses dry, activated manganese dioxide in a dilute fluidized-bed reactor to contact the flue gas and remove SO_2 by forming $MnSO_4$. This type of contacting device is commonly called an entrainment reactor.

In the DAP-Mn Process, SO_2 is adsorbed by activated manganese dioxide and recovered as an ammonium sulfate by-product. Activated manganese dioxide is an unstiochiometric compound that has a great affinity for SO_2 at temperatures of 212 - 356°F.[39]

Advantages of the DAP-Mn Process are:

a. Low power consumption due to low pressure drop or draft loss;

b. Ease of system shut-down in an emergency, since the adsorber has no packing or internals;

c. The flue gas is treated after it leaves the power plant boiler air heater, thus making it unnecessary to alter the power plant layout;

d. Long life of the adsorbent (low attrition rate);

e. Use of carbon steel material for the gas treatment system in general; however, stainless steel is used for the slurry treatment facilities.

Disadvantages of the system are:

a. Need for a high efficiency (99.9% +) dust collector system downstream of the adsorber;

b. Possibility of some air pollution from manganese oxides residual in the effluent flue gas.

c. Requirement of considerable operator attendance (four men are required to operate the plant;[40]

d. Production of $(NH_4)_2SO_4$ by-product, which is difficult to market.

4. Grillo Mixed Metal Oxides Process.

This process uses manganese dioxide and magnesium hydroxide for adsorbing and recovering SO_2 from flue gas for conversion to sulfuric acid.

The adsorbent used is a mixture of manganese dioxide and magnesium hydroxide, which is first deposited on a carrier such as coke. The adsorbent, deposited on the carrier, is contacted with the stack gas (from the dust collector) in moving-bed adsorbers (two are usually used). The adsorbent reacts with the SO_2 present to form manganese sulfate and magnesium sulfate. The adsorbent next is removed from the coke by shaking and screening, and the coke is recycled. A cyclone separator is used to separate the adsorbent from the effluent gas stream. The loaded adsorbent is then regenerated by mixing it with pulverized coal and heating both to about 1650°F to reduce all of the sulfur compounds to S^o, H_2S and/or COS. The sulfur-rich gas stream is subsequently burned to give a rich stream of SO_2, which may be fed to a sulfuric acid plant. Now in the oxide form, the calcined adsorbent is quenched in water to hydrate the alkaline earth (magnesium), and the slurry is deposited on the coke to complete the cycle.[41]

Advantages of the process are:[41,42]

a. Adsorbent attrition is quite low; i.e., adsorbent life is long.

b. Construction may be of carbon steel material.

c. The slurry deposited on the coke carrier is very reactive and adsorbs SO_2 rapidly.

The only known disadvantages of the process are the need to cool the flue gas partially (draft loss) and the experiencing of a small pressure drop through the carrier (coke) bed.[41] Neither is considered to be a serious drawback.

5. Still Lignite Ash Process.

This process uses the ash produced from lignite coal combustion as the adsorbent. Hydration of the lignite ash converts its high lime content (40 - 50%) to calcium hydroxide. Gas from the power plant dust collector is contacted by the adsorbent in a series of three countercurrent entrainment reactors. The SO_2 reacts to form calcium sulfites (mostly) and sulfates. The flue gas from the process enters an electrostatic precipitator for final removal of particulate matter. The spent ash is heated to yield a rich stream of SO_2 suitable for feed to a standard sulfuric acid plant. The regenerated adsorbent is recycled to the reactors. There have been problems with the calcium sulfate present fouling the adsorbent. In areas where lignite ash is readily available and can be purchased at a low price, however, the desulfurized adsorbent material could possibly be discarded, and fresh hydrated ash could be added to the reactor.

A test unit in 1967 attained SO_2 removals of 80% or better.

Investment costs for the process are said to be lower than those for the German Reinluft Process. Operating costs for the Still Process, in relation to power generation are reported to be very low, 0.5 mill/kwh.

Advantages of the Still Process are low adsorbent cost, low pressure drop, elimination of corrosion, and limited cooling of the flue gas. The major disadvantage known at present is sulfate fouling of the regenerated adsorbent.[41,42]

B. Wet Absorption Processes.

Wet absorption is considered to be the most popular SO_2 removal system in a number of processes under development. In a survey commissioned by the American Petroleum Institute (API), all SO_2 removal processes under development were reviewed and ranked according to state of development, technical feasibility, economic factors, advantages, etc.[43]

1. Wet-Limestone or Dolomite Processes.
    a. Combustion Engineering Process (C-E Process).

Basically, the C-E Process sonsists of the introduction of an alkaline earth additive into the furnace, followed by wet scrubbing. In the furnace of the boiler, the limestone and/or dolomite additive is calcined to the more reactive CaO and/or MgO; it reacts with the flue gas forming compounds of calcium or magnesium sulfites and sulfates. In so doing, it removes all of the SO_3 present and 20-30% of the NO_x present. The system reduces high-temperature liquid-phase corrosion by limiting the reaction of complex alkali ion trisulfates [$Na_3Fe(SO_4)_3$ and $K_3Fe(SO_4)_3$] with the boiler tubes and the alloy superheater materials. By removing SO_3, the cold-end corrosion problems in the air heater region are eliminated, and lower exit gas temperatures or reduction in the steam coil air heating requirements can be realized. In the C-E Process an overall removal of greater than 90% of the SO_2 and about 99% of the particulate matter is achieved.[44]

Difficulties experienced and some of the disadvantages of the C-E Process are:

1. Appreciable deposits of fly ash and additive material at the scrubber inlet and on the scrubber walls have been found (at Meramec).
2. Inlet gas distribution to the scrubber was found to be a problem. Plugging of the gas marble bed in the scrubber also occurred (at Meramec). Installation of

turning vanes in the lower section (under the marble bed) of the scrubber eliminated these problems.

3. A new limestone feeder drive assembly for better control of the addition rate was installed at Meramec.
4. Buildup of calcium sulfate deposits on boiler tubes has been reported to be a potential problem. This could possibly be alleviated by using a fluidized-bed combustion system (new boilers).
5. Solid disposal (fly ash and precipitates) from the clarifier or settling tank can present a real problem. Gypsum piles could become an eyesore.
6. The process does not produce a salable by-product.

b. A.B. Bahco Process.

This process is offering a version of the limestone scrubbing process which is said to remove about 98% of the SO_2 from the flue gas.[45] In this process, a two-stage scrubber system utilizes a solution of hydrated lime and water to remove SO_2. The sludge produced consists of about equal parts of $CaCO_3$ and $CaCO_4$, with some limestone. This sludge is said to be harmless enough to be dumped. However, there is the possibility that sludge disposal could lead to water pollution problems.

c. Zurn Processes.

Zurn Industries offers various SO_2 wet scrubbing systems, each unique and applicable to small and/or medium sized coal-fired boilers. The guaranteed conditions offered by Zurn are 98% particulate removal and 85% SO_2 removal. Unique in this process is the scrubbing slurry, which will be a combination of sea water and pulverized native coral marl. Underflow from the scrubber will contain $CaSO_3$ and unreacted marl. It will be piped to a lagoon, where the $CaSO_3$ will settle and be oxidized to $CaSO_4$. The gypsum produced landfill.[46]

Disadvantages of this system are: (a) production of a solid waste which will present disposal problems; and (b) lack of production of a salable by-product from recovered SO_2.

d. Universal Oil Products.

Three process schemes are offered: (a) Turbulent Contact Absorber, which may be used to scrub flue gases with aqueous solutions of soda ash (Na_2CO_3), hydrated lime ($Ca(OH)_2$), or a limestone slurry ($CaCO_3$); (b) Shell Flue Gas Desulfuring Atiom, which employs a solid, fixed bed of SO_2 acceptor (copper or alumina) in a reactor designed such that particulate matter need not be removed first to avoid bed plugging; and (c) Sulfoxel Process, which uses two wet scrubbing steps in the "absorber section of the plant: a Venturi scrubber and a Turbulent Contact Absorber Unit."[47,48]

These three processes exhibit removals of SO_2 from 90 to 97%.

2. Stone and Webster/Tonics Process.

The Stone and Webster Engineering Corporation and Tonics, Inc. have developed a new process which uses an aqueous caustic solution (NaOH) to remove SO_2 from the flue gases. The resulting sodium bisulfite solution is stripped to yield pure, dry SO_2, which goes to a sulfuric acid plant. The sodium sulfate solution from the stripping operation is sent to an electrolytic cell. Here, use of a special membrane, developed and patented by Tonics, enables the cell to produce caustic soda (NaOH), sodium acid sulfate, dilute sulfuric acid, oxygen and hydrogen. The electrolytic cell uses electricity from the power plant. The system is reported to remove and recover 90 - 95% of the SO_2 in the flue gases.

3. Peabody Soda Ash Process.

Peabody Engineering Corporation has developed a wet-scrubber system which can utilize various solutions of alkaline absorbents to remove SO_2 from flue gases. They use the soda ash (Na_2CO_3) in the main version of their process. Past tests conducted by Peabody, using their wet-scrubber methods, have demonstrated removals of 99.8% of the SO_2, 99.1% of the particulate matter, and 25% of the nitrogen oxides present in the flue gases from certain boilers.[49] Peabody claims the use of soda ash as an absorbent can remove essentially all the SO_2 present.

The Peabody Process has the two disadvantages so common to many wet-scrubbing methods: (a) relatively high operating cost for chemical makeup; and (b) production of a solid waste which must be disposed of.

4. Hitachi Caustic Soda Process.

Hitachi, Ltd., has developed a flue gas desulfurization process in Japan.

The flue gases are contacted with an aqueous caustic soda (NaOH) solution in a reactor (scrubber). The Na_2SO_3, plus any other reaction products, is dried to a powder by sensible heat of the flue gases. There are no liquid wastes or other by-product streams. The process appears to be quite simple. However, the market for Na_2SO_3 appears to be quite limited.[50]

5. Chiyoda Process.

The Chiyoda Process has three basic stages: (a) absorption; (b) oxidation; and (c) crystalization. After scrubbing with water, the flue gas goes to the absorber, where a recirculating stream of dilute sulfuric acid absorbs the SO_2. The treated gas leaves the absorber, is reheated by a burner, and passes on to the stack. The acid bottoms from the absorber flows to the oxidizer, where air is blown into the tower. The oxidizing catalyst is an inexpensive, nonpoisonous compound that is soluble in the acid. Part of the acid goes from the oxidizer back to the absorber, while the rest goes to a crystallizer. Limestone is mixed with the acid solution in the crystallizer to form gypsum of the crystals. The mother liquor and wash water are recycled to the absorber. The gypsum crystals may be dried and stored. There are no waste effluent streams from the process. Commercially usable gypsum is the by-product produced from the process.

Chiyoda claims that the process is nonclogging, and inexpensive to install and operate, and has high process flexibility. They claim SO_2 removals for certain applications.[50]

C. Catalytical Oxidation Processes.

This is perhaps one of the simplest approaches to SO_2 recovery from stack gases. These processes involve the catalytic oxidation of SO_2 to SO_3 in the stack gas stream. The SO_3 can be recovered easily, without absorbent recycling and with little or no cooling of the flue gas. The main disadvantage of this method is that the high temperature required for catalysis (about 850°F) requires that the catalytic converter be installed ahead of the economizer. Also, very efficient particulate removal is required before the gas contacts the catalyst bed. The electrostatic precipitator must therefore be quite large, since it must operate at a high temperature.

1. Monsanto Cat-Ox and Other Processes.

a. Cat-Ox Processes.

In the Integrated Cat-Ox System, hot flue gas at about 850°F is taken directly from the power boiler and flows to the electrostatic precipitator. Hot gas from the precipitator flows directly to the catalytic converter, where about 90% of all the SO_2 is oxidized to SO_3. This system is designed so that the proper conversion is maintained over a wide variation of boiler loads. When the boiler load is cut to 50% of design, the Cat-Ox conversion of SO_2 to SO_3 is still about 80%. Relatively rich in SO_3, flue gas from the converter is cooled in an economizer and a boiler combustion air heater. The economizer is a finned-tube type of exchanger used to preheat boiler feed water. In this unique position, following the dust collection equipment, both the economizer and air heater operate in a cleaned-gas atmosphere and do not incur erosion from fly ash abrasion. Both of these exchangers are operated above the dew point of the H_2SO_4 present, which eliminates or reduces the problem of corrosion.[52]

An Integrated Cat-Ox System will remove 90% of the SO_2 and essentially all of the fly ash from the flue gas.

b. Calsox Process.

This is a throw-away process which produces calcium sulfate as a solid by-product. Sulfur compounds are removed from the system by the addition of "milk of lime" in a two-stage reaction-settling system.[52]

In a pilot plant operation, the Calsox process effectively removed 90% of the SO_2 from a flue gas containing 1500 ppmv (parts per million by volume) of SO_2 at 120°F and saturated with water.[53]

c. Nosox Process.

In the Nosox Process, SO_2 is absorbed from the flue gas in a water-soluble organic material (proprietary absorbent) and then steam stripped from the absorbent during regeneration. Clean flue gas leaves the Nosox absorption tower with an SO_2 content of about 200 ppmv.[53] The cleaned gas from the absorber passes to the stack. Also, essentially all of the fly ash is removed.

2. Kiyoura I.I.T. Process.

This is another version of the catalytic oxidation process. In this process, high temperature flue gas passes through an electrostatic precipitator and flows through a V_2O_5 catalytic converter, to the boiler economizer, and then to the air preheater. Ammonia is injected into the gas stream between the economizer and the air preheater. The gas temperature is closely controlled at 220 - 260°C at this point to ensure production of pure $(NH_4)_2SO_4$. The NH_3 reacts with the SO_3 and available H_2O, forming solid $(NH_4)_2SO_4$. Mechanical collection (filtration or equivalent) of the $(NH_4)_2SO_4$ after the air preheater produces the by-product. The cleaned flue gas then flows to the stack. This method avoids acid condensation on the preheater.[37] Results have shown 93% removal of SO_2.

D. Wet and Dry Adsorption Processes.

1. Lurgi Sulfacid Wet Process.

In this process, flue gases from the fly-ash removal step (if required) are contacted with weak H_2SO_4 in a packed tower, as a prelude to conversion of the SO_2 to SO_3 in the reactors. Weak acid produced from the process is concentrated by this step, and the incoming gas is cooled to the proper reactor temperature of 140 - 158 F. By-product acid thus strengthened to 70 wt% H_2SO_4 can be used in the production of fertilizers, steel pickling operations, and/or leaching of ores. In the packed tower, the acid tends to pick up impurities from the gas.

Lurgi fabricates their sulfacid scrubbers from a carbon steel framework, lined with rubber or lead sheeting. In high-temperature zones, the shell material is protected by a refractory lining. Their reactors are usually carbon steel, horizontal vessels which are rubber-lined or plastic-lined.

Sulfur dioxide removal efficiencies have been found to be in the range from 91 to 98%.[53,54]

2. Hitachi Wet Process.

This is another version of the carbon adsorption method of

SO_2 removal of the Hitachi Process, developed by Hitachi, Ltd., of Tokyo, Japan.

As in the Lurgi Sulfacid Wet Process, the H_2SO_4 formed on the carbon is washed away by water. In this process, the carbon adsorbent is contained in six reactors (towers) which are operated in a cyclic manner. A single tower goes through a cycle of 30 hr of absorption, 10 hr of washing, and 30 hr of drying. Uncovered flue gas from the dust collector or air heater flows to the tower on "washing." In the tower on "drying," the cleaned stack gas passes first through the wet tower and then through a dry tower that removes any acid mist. Minimal flue gas cooling is a main objective of the process.[37]

An SO_2 removal efficiency of 90% has been reported.

3. Reinluft Dry Process.

This process uses a slowly moving bed of activated char, formed from a "semicoke," carbonized under vacuum at 1100°F. In this dry-adsorption method, low-dust-content flue gas passes through a two-stage countercurrent adsorber vessel. The flue gas, at a temperature above its dew point, enters the first stage, where the coke adsorbs the SO_2 and sulfuric acid mist (if present). The flue gas is then drawn off (at 290°F), cooled to 200°F and then fed to the second stage. The gas is cooled to enhance the oxidation of SO_2 to SO_3, which proceeds more readily at a lower temperature. Ultimately, the SO_2 in the flue gas is oxidized to SO_3 and adsorbed with water in the char (coke) to form sulfuric acid. The cleaned flue gas exits from the Reinluft reactor at about 215°F and flows to the stack.[38]

Removal efficiencies for SO_2 of better than 95% have been reported.

4. Sumitomo - Kansai Adsorption Process.

This process takes place in three different steps: (a) adsorption of SO_2 on the carbon; (b) separation of the SO_2 from the carbon by heating and use of an unspecified inert stripping gas; and (c) conversion of the separated SO_2-bearing gas to 98 wt% H_2SO_4 in an acid plant.

Early tests in 1970 have shown 80 - 85% SO_2 removal from flue gas from an oil burning (2 wt% S) boiler.[55]

History of the Project

Several studies have been performed since 1975 to investigate the behavior of surfactant solutions (water-surfactant solutions) as means of enhancement for organic removals, at the Environmental Laboratory, New Jersey Institute of Technology.

Following, in chronological order, are the difficulties and achievements found by different investigators:

1975: A.C. Moressi[56] performed static tests with aqueous solutions of surfactant and organic vapors "in vitro." Vapor pressure of organic above the solution was measured at the beginning and 24 hours later. The vapor pressure differences of this solution and blank solutions were compared, and results were promising.

1977: F.C. Matunas[57] conducted experiments with forty different surfactants at six concentrations, on five organics at two concentrations. The organics tested were toluene, benzene, carbon tetrochloride, p-xylene, and acetone. Dynamic conditions were maintained to study the solubilizing effects of surfactants in a countercurrent packed scrubber. Excessive foaming conditions were the main problem. Changes in the system did not improve the results, so Matunas built packed tower scrubber II with additional foam reservoirs. Results at this point were better and showed the method to be a very efficient technique.

1978: A.M. Bodnarik[58] performed tests on twenty-three surfactants (those which exhibited superior removal) and various chlorocarbons and fluorocarbons. Experiments were performed in packed tower scrubber II.

D. Berlinrut,[59] later in the same year, built packed tower scrubber III, keeping the same conditions except for the installation of foam compression chambers. He performed tests with homogeneous mixtures of the organics used earlier. The system was designed to handle air flows in the 200 to 300 cfm range. Scrubber III proved to be an effective tool in controlling the emissions of the spray lacquer solvents.

1979: I. Atay[60] built an ejector venturi scrubber. This scrubber was designed for 30 gpm liquid flow rate with a corresponding gas flow rate of 300 cfm. During all the tests the maximum liquid flow rate obtained was 11.8 gpm, which was less than one half of the design value. Atay performed tests with four surfactants and five organic vapors. The organics were: acetone, p-xylene, carbon tetrachloride, toluene, and benzene. Foaming conditions were not significant as those found in the packed tower scrubber. Flooding did not appear to be a problem as it is in the packed tower. No limit to the liquid to gas ratio (L/G) was found because of the loading or flooding point pressure drop consideration. High liquid to gas ratio and sufficient residence time are required to achieve satisfactory removals.

1981: The author performed several experiments by using the ejector venturi scrubber technique. The subject of the investigation was the removal of sulfur dioxide from air exhaust streams by means of surfactant scrubbing solutions. Results were promising; however, foaming conditions were, in some cases, the limiting factor in the improvement of efficiencies. Better removals could be obtained by using surfactants with lower foaming tendencies.

Statement of the Problem

The Sulfur Dioxide Emissions Problem

Of the major contributors to air pollution, such as carbon monoxide, particulate matter, oxides of nitrogen, and unburned hydrocarbons, particular emphasis has been placed on sulfur dioxide emissions from industrial operations. Local legislation restricting the sulfur content of fossil fuels has all but proscribed the use of available coal and heavy fuel oils in many areas.[61]

Recent estimates by the U.S. Environmental Protection Agency (EPA) place sulfur oxide (SO_x) emissions at about 26 to 30 million metric tons per year. Most of the SO_x emissions come from a relatively small variety sources. About 80% of all emissions are from stationary source fuel combustion and about two thirds of all emissions are from the electric utility industry. The remaining 20% can be primarily attributed to a few industrial processes: metals smelting and refining, petroleum refining, mineral products processing, and chemicals manufacturing. Approximately 60% of the industrial emissions are attributable to the metals industries, with the remainder being divided somewhat evenly among the other three areas.

Nationally, SO_x emissions are being stabilized and even showing a slight downtrend, from a total of 29.1 million tons in 1970 to approximately 26.9 million tons in 1976. The downtrend is largely due to lower emissions from the industrial process sources. These sources show a reduction of one third between 1972 and 1976, mainly in the metals smelting and refining area. It is obvious that adequate control of SO_x in our atmosphere will depend on control of SO_x emissions in combustion exhaust gases.

Numerous approaches to solution of the sulfur dioxide air pollution problem have been proposed. These generally fall into the following categories:

1. Elimination of fossil fuels completely;
2. Stack gas cleanup
    a. Wet scrubbing,
    b. Dry treatment;
3. Use of alternative fuels;
4. Desulfurization of fossil fuels.

Unless present plants are altered, the impending energy crisis coupled with enactment and enforcement of increasingly stringent legislation regulating fuel oil sulfur content are expected to result in a serious imbalance in residual fuel oil demand versus availability beginning in the next few years and extending into the foreseeable future.

Commercially proven hydrodesulfurization technology such as the UOP RCD (service mark of Universal Oil Products Company) Isomax process is presently available for production of residual fuel oils in the range of 1.0 wt % sulfur. Modification of existing techniques will permit, for most crude oils, production of heavy fuels meeting tomorrow's regulations.[62]

Wet Scrubbing Techniques

Wet scrubbing techniques are currently used in many air pollution control processes. Both gaseous and particulate contaminants can be handled by using these techniques. Different types of wet scrubbers have been designed, including spray towers, wet cyclones, venturi collectors, perforated impingement trays, nucleation scrubbers, turbulent contactors, wet filters and packed towers.

Some important parameters must be considered to estimate removal efficiencies in wet scrubbers: residence time of the air stream, available contact areas, the solubility of the component to be removed in the liquid phase and the concentration of contaminant in the inlet gas stream.

Water and dilute aqueous solutions are used as scrubbing liquors for a wide range of gaseous contaminants. Extensive research rests upon treating of gases that contain inorganic compounds, water soluble inorganics, and water soluble organics.

The Use of Surfactants in Scrubbing Liquors

Surfactants, as mentioned before, exhibit good scrubbing characteristics which are used to remove gases from air streams. Surfactants also have the ability to alter the solvent's surface tension and/or affect the interfacial tension between two liquids.

Some accomplishment has been obtained in organic vapors removal when surfactants are added to scrubbing liquor. Matunas, F.C.[57] and Bodnarik, A.[58] found a substantially enhanced solubility of organics normally immiscible in aqueous systems.

Plevan and Quinn[63] measured the permeability (or surface resistance of various monolayers) to gases, as well as their effectiveness in hindering any substrate motion which accompanies the absorption process. Results are reported for sulfur dioxide absorbing into water and into aqueous gels in the presence of surface-active agents.

EXPERIMENTAL

The Ejector Venturi Scrubber

The pilot scrubber used in this research was the ejector venturi scrubber of the Crolf-Reynolds Co. The system was designed for 30 gpm liquid flow rate with a corresponding gas flow rate of 300 cfm. The separator tank of the scrubber was of the mist eliminator type.

The ejector venturi scrubber system was completed by Atay[60] at the end of October 1979.

The ejector venturi scrubber system (see Figure 1) is mainly composed of: (a) separator tank, (b) ejector venturi, (c) pumping system (including piping and fittings), (d) inlet air line, and (e) foam destruction tanks.

Following is a brief description of the system:

(a) Separator tank: The dimensions of the separator tank are 6'4" height and 24½" diameter. A clear plastic window permits the inspection of the foaming characteristics of the surfactant solutions. Tap water inlet and surfactant injection ports are used to prepare the surfactant solution required for each run. The separator tank, therefore, is used as the scrubbing solution recycle reservoir.

(b) Ejector venturi: The ejector venturi (see Figure 2) in this system is used to both move the gases and scrub them in one corrosion resistant unit. In the Crolf-Reynolds Jet Venturi Fume Scrubber, the flow of the gases is parallel to the water giving intimate contact between them. As the motivating liquid passes the spinner, it is given a centrifugal twist so that it forms a hollow cone spray. The shape of the cone is designed to give maximum scrubbing action between the motivating liquid and the gases or vapors and still maintain a high degree of motivating force. The pressure in the unit is so slight that any material that is self-supporting can be used. The motivating liquid enters "A," where it flows past the spinner "B" and out of the orifice "C." Here the high velocity motivating liquid entrains the gases or vapors entering suction "D" and discharges both the motivating liquid and the gases through the outlet "E."

(c) Pumping system: A Flotec Centrifugal Pump with fluid jacketed seal was used. The choice was made to have a resistant corrosion impeller because of the acidic liquor flowing through the system. The pump horsepower is 1.0 hp. The maximum liquid flow rate obtained during test runs was 8.5 gpm, and the maximum air flow corresponding to this liquid flow rate was 1000 ft/min.

The dimensions of the inlet and outlet lines of the pump and the flowmeter (liquid flow meter) were 1¼" and 1½" respectively, to provide the least frictional loss. The number of elbows and tees were kept to the minimum number possible, in order to further decrease the frictional loss.

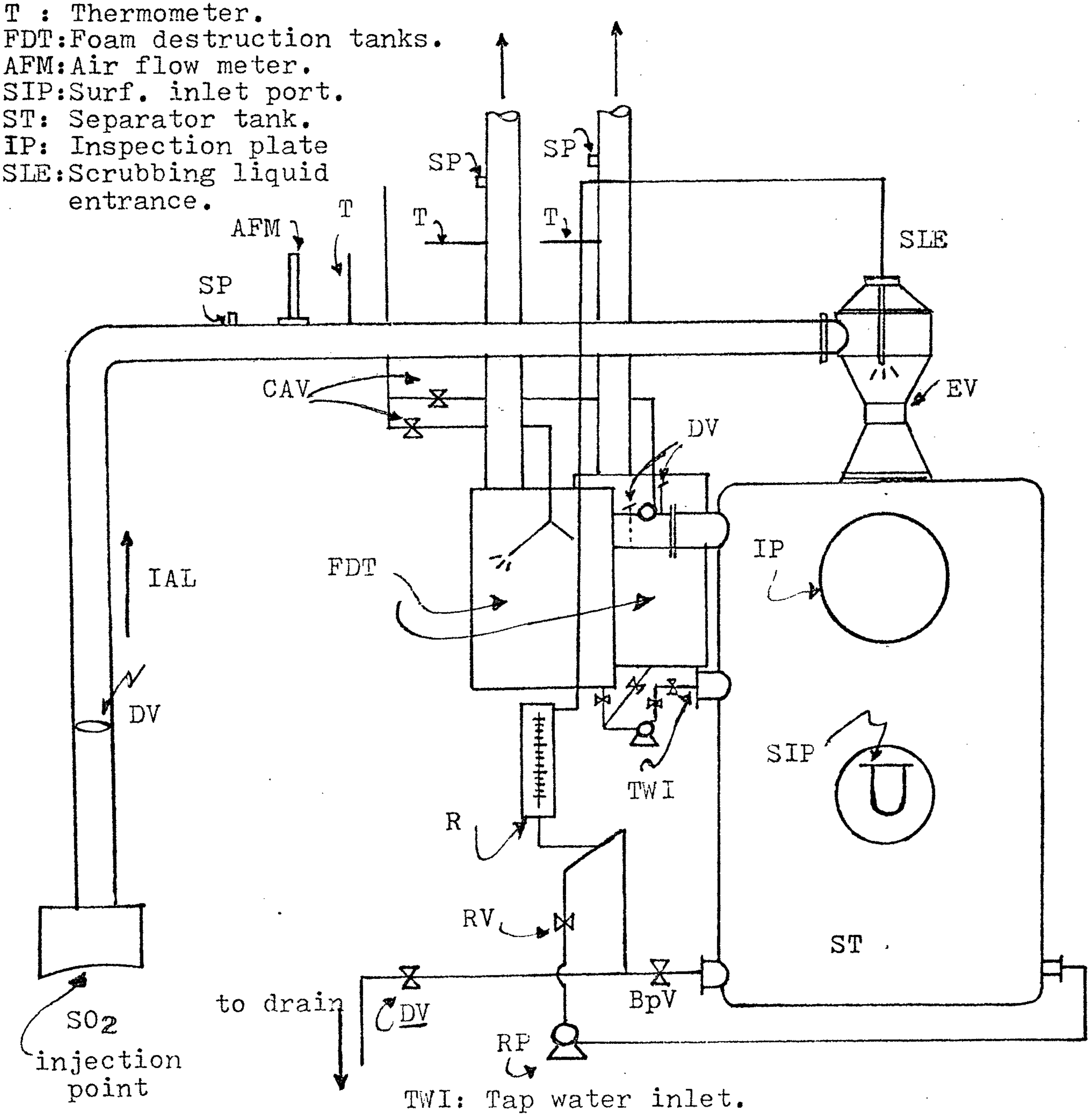
(d) Inlet air line: The inlet air line, 4" diameter, is connected to the converging section of the ejector venturi. A damper was installed in this line to vary the air flow inlet. This makes it easy to have variations in the liquid-to-gas ratio (L/G).

(e) Foam destruction tanks: A foam destruction system was designed. Two reservoirs with compressed air nozzles were installed to the air exhaust port of the separator tank, and two exhaust air pipes were built on them. Each reservoir was a foam destruction system by itself. They were designed to be used in sequence. The compressed air nozzles, used in the reservoirs, are standard rotary lawn sprinklers. These nozzles blow an air stream which is parallel to the foam surface, which in turn destroys the foams contacting the air stream by throwing it against the walls of the reservoir. The air compression cannot be used when taking samples, because of the dilution effect. Therefore, when one of the reservoirs is filled with foam, the exhaust air coming out of the separator tank is diverted towards the other reservoir. The foams in the first reservoir are compressed and pumped back to recycle. A pump and two return valves were installed connecting the foam chambers to the tap water inlet port of the separator tank.

Figure(1)

The Ejector Venturi Scrubber System.

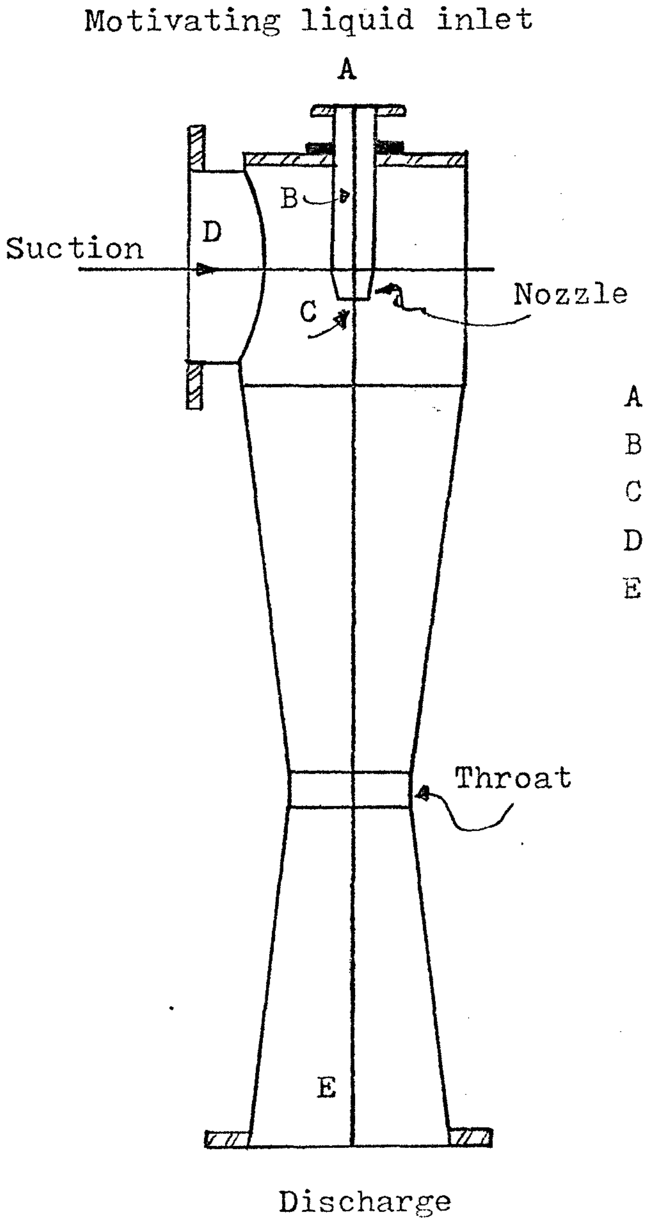
EV: Ejector venturi.
DV: Damper valve.
IAL: Inlet air line.
CAV: Compressed air valves.
SP: Sampling port.
T : Thermometer.
FDT: Foam destruction tanks.
AFM: Air flow meter.
SIP: Surf. inlet port.
ST: Separator tank.
IP: Inspection plate
SLE: Scrubbing liquid entrance.



TWI: Tap water inlet.
R : Rotameter.
DV : Drainage valve.
RV : Recycle valve.
BpV: By-pass valve
RP : Recycle pump

Figure(2)

The Ejector Venturi.



A: Liquid inlet
B: Spinner
C: Orifice
D: Gas inlet.
E: Outlet

Experimental Procedure

This section deals with the procedures which were followed when tests were performed with the ejector venturi scrubber. The preparations and the execution of the experiments as well as the maintenance of the system are explained.

The preparation for a test takes approximately one hour. First, the sulfur dioxide sensing electrode is plugged into the voltmeter. It is ready for use in 30 minutes. The procedure for handling the sensor electrode can be found in the related section.

The separator tank is filled with tap water at a level higher than the suction end of the pump. This provides efficient operation of the recycle pump by preventing the passage of air bubbles through the pump. The drainage valve is kept closed during this operation and during the time the test is taking place. The by-pass valve is kept open while filling the tank and closed during the running. The volume of the solution used in all the tests was 82.25 gallons. When three quarters of the required volume is obtained, the proper amount of surfactant is added through the surfactant inlet port. Then by adding more water, the volume of the solution is completed to 82.25 gallons.

Special precaution is necessary when operating the pump. The discharge valve of the recycle pump is kept closed when the system is off, and it should be closed before shutting the pump off in order to prevent backturning of the pump by the solution falling down the pipes. Running in reverse may cause the impeller to spin off. During the initial start up, the discharge valve is kept closed. It is opened gradually as the motor develops full r.p.m. This allows a gradual build-up of power requirement. If the pump does not build up pressure as the motor develops speed, the system is shut down and reprimed. The recycle pump should never be primed while it is in operation.

The air flow meter, located in the inlet air line, is turned on and calibrated for zero air flow with the cap covering the air flow sensors.

Then the cap is taken off, and the flow meter is installed on the polluted air inlet line with the sensors facing the flow perpendicularly.

After the surfactant solution is prepared and the recycle pump is primed, the by-pass valve of the separator tank is closed and the drainage valve is rechecked for closeness. Damper valve (2) of the foam reservoir (2) is closed, and damper valve (1) of the foam reservoir (1) is kept open. The flow through air sampling ports is checked by using a calibrated rotameter. Air samples are taken by bubbling the polluted air into alkaline solutions (pH > 11.0) during a five minute period, five minutes having elapsed between two consecutive samples. Sampling time must be maintained as constant as possible and recorded to calculate the volume of air according to the rotameter reading. Procedures to calculate the sulfur dioxide concentration in samples (ppm) is described in the related section.

The recycle pump is started, and the surfactant solution is passed through the system for five minutes in order to distribute the surfactant evenly in the liquid phase and reach steady-state conditions. When the solution is ready, the sulfur dioxide valve is opened and regulated. A rotameter is installed in the sulfur dioxide line to measure the concentration which is being injected (inlet concentration).

The run starts as soon as the sulfur dioxide is injected into the inlet air line and lasts for 50 minutes. Inlet and outlet temperatures must be recorded for every sample. During the run, a close eye is kept on the foaming conditions through the mirror placed on the control platform. When the first chamber is full, the valve leading to that chamber is closed, and the valve of the other chamber is immediately opened. Thus, the air flow is diverted to the latter chamber. The compressed valve of the full chamber is opened, the foams are broken, and the liquid is returned back to the separator tank by means of the foam return pump.

Once the run is terminated, the sulfur dioxide valve is shut. Next, the recycle pump is turned off. Care must be taken while shutting the recycle pump off. First of all, its discharge valve should be closed followed by immediate shutting of the pump. The drainage valve is fully open and the by-pass valve is half-open while draining the separator tank in order to prevent back-up from the drainage piping.

Air samples are analyzed as described in the related section. The air flow meter is shut off, and the cap of the sensors is put on. The separator tank is filled with tap water, then it is run through the injector venturi to clean the traces of surfactant left. If the next run is with the same surfactant, washing three times with tap water is sufficient. If the surface active agent is to be changed, the washing operation should be repeated until no foams are seen on the surface of the liquid inside the tank. The foam reservoirs are washed by filling with tap water and draining several times.

When the cleaning operation is terminated, all the valves, except the tap water valve and the discharge valve of the pump, are opened; all the switches and electrical connections are rechecked.

The Sulfur Dioxide Sensing Electrode

The Model GS-136 Sensing Electrode is used to measure the concentration of sulfur dioxide in aqueous solutions using an expanded scale pH/millivolt meter. Anions, cationics and other dissolved solids do not interfere with sulfur dioxide measurements. The sulfur dioxide electrode may have minor interference due to volatile weak acids such as acetic acid. Great operating ease and quick response are two important features in this device. (See Figure 3)

Concentrations from 0.5 to 1000 ppm can be detected with Model GS-136. Successive dilutions in samples allow to get higher reading concentrations.

Operating procedures of the GS-136 sensing electrode:

A. Electrode Assembly.

1. Remove orange cap from electrode body and rinse glass sensing element and reference electrode with distilled water. Use plastic wash bottle with narrow spout to inject distilled water into reference compartment and thoroughly rinse this compartment. Pour out residual distilled water from probe. The reference electrode is a dark colored wire surrounding the glass electrode.
2. Inject filling solution into reference compartment. Remove filling solution from the reference compartment by turning electrode body upside down and shaking body vigorously with one hand. Inject additional filling solution into reference compartment until solution completely fills this compartment. Add additional drop of filling solution to cover glass sensing element.
3. Remove membrane from membrane box using special tweezers supplied with kit. Place membrane into inverted electrode cap. Push O-ring into cap so that membrane sits between the cap and the O-ring.

4. Carefully force cap onto electrode body so that membrane fits snugly over glass sensing element. Glass element should protrude slightly through top of cap.
5. Allow electrode to soak in 0.01 molar sodium bisulfite for thirty minutes before use.

B. Standardization.

1. Prepare primary sulfur dioxide standard solution as follows: Using a one-liter volumetric flask, add 1.625 grams of reagent grade sodium bisulfite. Add distilled or deionized water to give exactly one liter. Mix well. Store in sealed container. Concentration of this solution is 1000 ppm. Prepare fresh solution every three weeks.
2. Prepare standards (100 ml solutions) between 0.1 and 1000 ppm by diluting primary standard (suggested solutions in ppm: 0.1, 0.3, 0.5, 0.7, 1.0, 3.0, 5.0, 7.0, 10.0, 30.0, 50.0, 70.0, 100.0, 300.0, 500.0, 700.0).
3. Connect electrode plugs to expanded scale pH/millivolt meter whose input impedance is at least 10^{12} ohms.
4. Immediately before measurements, add 1.0 ml sulfuric acid (1.0 ml concentrated H_2SO_4 per 100 ml of solution) to convert bisulfite ion to sulfur dioxide. Acid should only be added immediately before measurements to prevent loss of sulfur dioxide to air.
5. Immerse electrode into first standard (lowest concentration) being careful not to trap air bubbles underneath electrode cap. Stir solution at a constant rate which provides convection but does not cause bubbles to form underneath electrode (to minimize bubble formation place electrode at slight angle to vertical axis). After allowing electrode to stabilize, record millivolt reading. Proceed in a similar manner with next standards which have slightly higher concentration, e.g., follow the order: 0.1, 0.3, 0.5 ... up to 1000 ppm.

6. Plot millivolts vs. sulfur concentration on semilog paper. The concentration axis should be the log axis. Draw best straight line through points. (See Figure 4)

C. Measuring sulfur dioxide in unknown sample.

As it was stated, the model GS-136 sensing electrode is used to measure the concentration of sulfur dioxide in aqueous solutions. Following, procedures to find the sulfur dioxide concentration in air samples are listed:

1. Collect air sample by bubbling contaminated air through scrubbing solution (100 ml distilled water plus sufficient sodium hydroxide to obtain pH ~ 10) during five minutes. Record the volume of air bubbled through the system. A calibrated rotameter is necessary to maintain a constant air flow rate.
2. After rinsing electrode with distilled water and blotting with tissue paper, immerse electrode into unknown sample after adding 1 ml of concentrated sulfuric acid to sample. Stir solution at same rate as standard solutions.
3. Monitor electrode potential and record stabilized potential reading.
4. Using electrode standardization curve prepared previously, read sulfur dioxide concentration of unknown sample.
5. Calculations to obtain the sulfur dioxide concentration in sample. Calculations are based on 100 ml scrubbing solution:
   a. Data required:

      Volume of air sample, liters, V_a;
      Number of moles of sulfur dioxide, in 100 ml sample, n;
      Volume of sulfur dioxide in 100 ml sample, liters, V_s
      (temperature correction is necessary);

   b. Concentration (ppm by volume) of sulfur dioxide in sample, C:

$$C = \left(\frac{V_s}{V_a}\right) 10^6$$

6. For best results, samples and standards should be at the same temperature.
7. Collected samples should be stored in closed containers to prevent loss of sulfur dioxide to air.

D. Electrode storage.

1. Between measurements the electrode should be kept in sulfur dioxide standardizing solution.
2. When not in use the electrode can be stored in sulfur dioxide standard solution (100 ppm).
3. If electrode is returned to storage, disassemble and rinse thoroughly with distilled water, particularly the reference compartment. Dry thoroughly and store with cap in place, but without membrane.

E. Troubleshooting.

1. Loose connection between electrode plugs and pH/millivoltmeter.
2. Torn membrane (characterized by shifting potential).
3. Electrode cap which has been forced on either too tight or too loose.

Figure(3)

The Sulfur Dioxide Sensing Electrode
(From LAZAR Research Laboratories.).

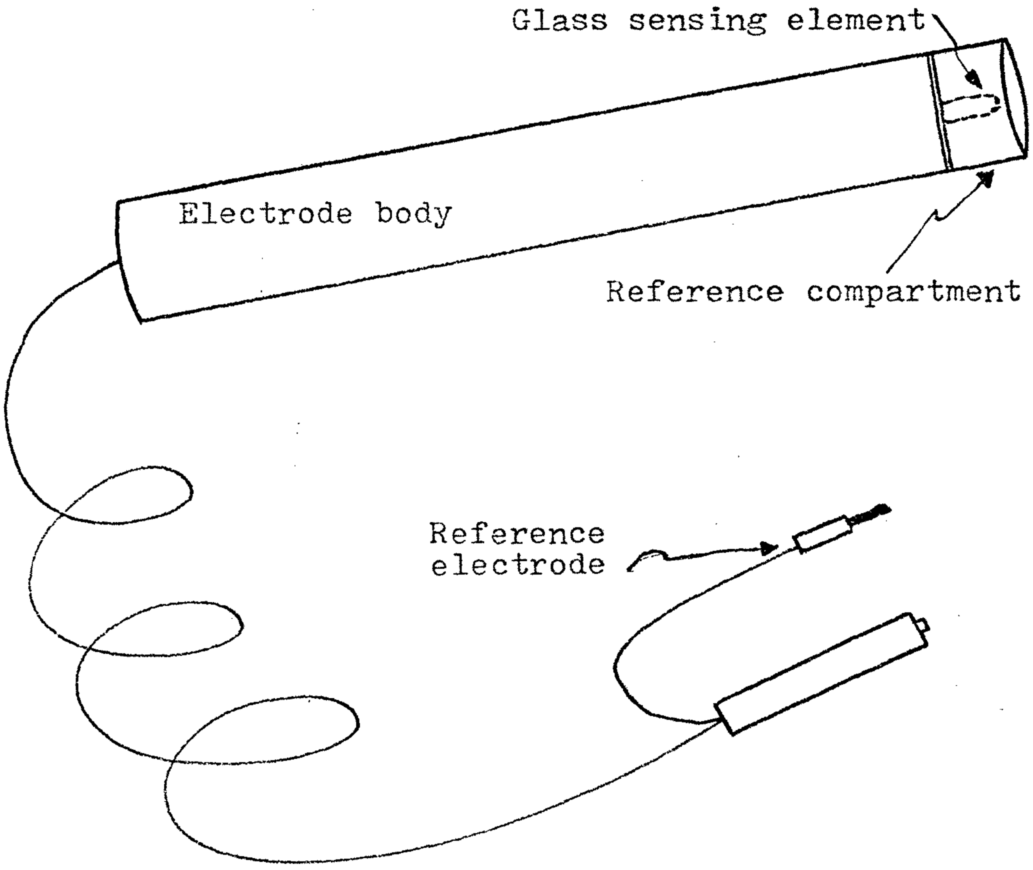
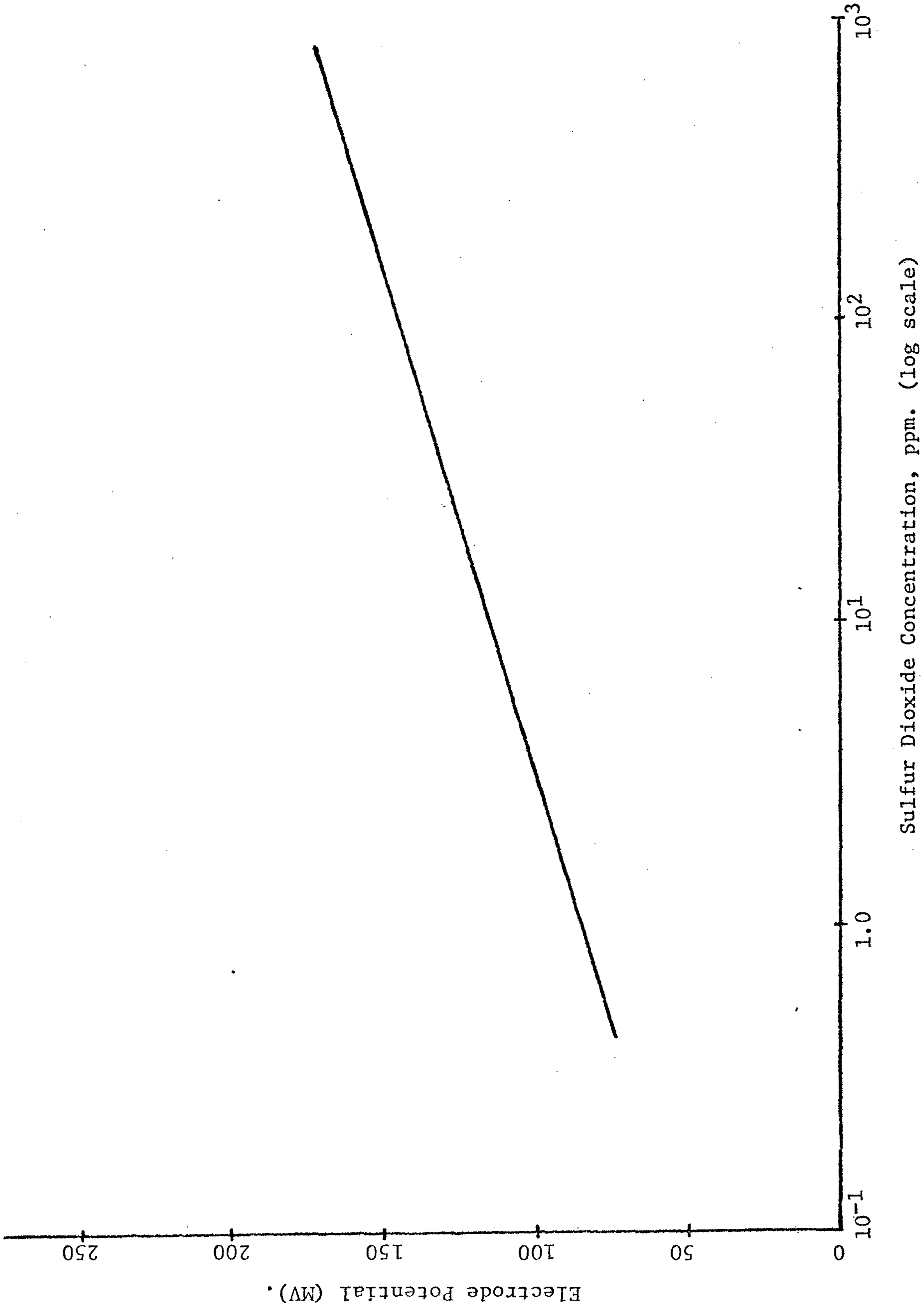


Figure (4)

Sulfur Dioxide Calibration Curve

Electrode Potential (MV) versus SO_2 conc., ppm.



Results and Discussion

This section deals with the results obtained with the ejector venturi scrubber technique used to remove sulfur dioxide from air streams.

As it was stated before, six surfactants were tested in the experimental phase to investigate their ability to enhance the solubility of sulfur dioxide from air streams. The criterion for selecting these surfactants was their behavior when acid solutions are to be handled as it is the case of sulfur dioxide. The surfactants used during the investigation were: Emulsynt 2400, Arsil 303-E, Mafo 13, Abex JKB, Cenetol HS, and Armohib 31. Table 3 shows characteristics of these products.

Preliminary tests were performed to determine removal efficiency when no surfactant is added, this is, with plain water. Tables 4 and 5 show results at 45.0 and 81.0 cfm. respectively. Results are slightly the same, being better at 45.0 cfm., but not enough to be significant. Differences can be related to the fact that an increase in liquid flow rate (from 5.3 to 8.4 gpm) creates a greater turbulence in the surfactant solution, causing escape of the gas. Air flow rates were main-

Before each surfactant was tested, a run was performed with plain water as a control. Results were similar to those shown in Tables 4 and 5 , so they describe average results.

Based on foaming conditions for each product (see Table 6 for foaming characteristics), the range of concentrations, in percent (%) by volume was selected. Air flow rates were maintained at 45.0 and 81.0 cfm. as extreme conditions.

Following, is a discussion according to results for each surfactant:

- Surfactant: Emulsynt 2400.

Concentration range: 0.01 to 0.15 % by volume.

Air flow rate: 81.0 cfm.

Heavy foaming was developed at 0.05 % concentration, and pumping problems arose when 0.15 % concentration was tested. Removal efficiencies ranged from 35 to 60 %. The 0.07 % concentration showed the best results. It was observed that when concentrations higher than these were used, the efficiency dropped drastically.

Air flow rate: 81.0 cfm.

Increasing removals were found when increasing concentrations of surfactant were used. No significant increment was observed When concentrations were changed from 0.05 to 0.15 %. As was expected, foaming conditions began to cause problems at lower concentrations than on the first case. The highest removal efficiency, 70 %, occurred at both, 0.07 and 0.1 % concentrations. Results are shown in Tables 7 trough 20 and Figures 5 and 6 .

- Surfactant: Arsil 303-E.

Concentration range: 0.01 to 1.0 % by volume.

Air flow rate: 45.0 cfm.

Arsil 303-E is a defoamer, so no problems developed at any concentration during tests. Removal efficiencies were found to be between 70 and 80 % for concentrations equal or less than 0.1 %. The lowest concentration in the range, 0.01 %, gave the best results, but a definite pattern was not followed as concentrations were gradually increased. Removal efficiencies dropped vertically when 1.0 % surfactant was used, to values lower than 38.0 %.

Air flow rate: 81.0 cfm.

Removal efficiencies of the order of 80.0 % were obtained with concentrations up to 0.03 %. At higher concentrations the efficiencies were lower than those found for 0.0 % concentration. There was a clear relationship between 1.0 % surfactant concentrations at both air flows, with efficiencies lower than 40.0 % in all tests. Results for Arsil 303-E are shown in Tables 21 through 34 and Figures 7 and 8 .

- Surfactant: Mafo 13.

Concentration range: 0.01 to 0.2 % by volume.

Air flow rate: 45.0 cfm.

Light foaming was observed at 0.15 and 0.2 % concentrations. Since removal efficiencies at these concentrations were not significant, tests were repeated for lower concentrations at which relatively high efficiencies were found in the order of 70 % at 0.01 and 0.02 concentrations. A definite decrease of removal efficiencies was observed when concentrations increased.

Air flow rate: 81.0 cfm.

A similar behavior was observed with this air flow; that is, efficiencies decreased with increasing concentrations. Very heavy foaming at concentrations higher than 0.1 % and efficiencies lower than 55 % (less than 50% at 0.2 concentration) made impractical the sulfur dioxide scrubbability. Figure 9 and 10 and Tables 35 through 48 show results for this product.

- Surfactant: Abex JKB.

Concentration range: 0.02 to 0.07 %.

Surfactant concentrations were maintained in a narrow range with this product due to the great foaming characteristics.

Air flow: 45.0 cfm.

A notable increase in removal efficiencies with increasing concentrations was observed when these ranged from 0.01 to 0.05%. The highest removal was found to be 80 % at 0.05 % concentration. Efficiencies beyond this concentrations dropped drastically to values close to the plain water curve efficiency.

Air flow rate: 81.0 cfm.

No definite pattern was followed with this air flow rate at different concentrations and foaming conditions were so great that no recommendation can be made for this product since efficiencies were less than 70.% for all tested concentrations in the proposed range. Results for Abex JKB are shown in Tables 49 through 62 and Figures 11 and 12.

- Surfactant: Cenetol HS.

Concentration range: 0.01 to 1.0 % by volume.

Air flow rate: 45.0 cfm.

Removal efficiencies varied from 50 to 80 %.; the highest efficiency occurred at 0.01 % concentration. There was a tendency at all tested concentrations to reach between 55 and 65 % removal efficiencies except for 1.0 % concentration which dropped down to 47 % efficiency. Foaming problems did not developed within the tested range of concentrations.

Air flow rate: 81.0 cfm.

Removal efficiencies increased with increasing surfactant concentrations from 0.01 to 0.07 % concentration. The efficiency at the latter concentration was 80 %. After this point efficiencies decreased and foaming problems appeared, making difficult to continue the experiments. Results are shown in Tables 63 through 76 and Figures 13 and 14.

- Surfactant: Armohib 31.

Concentration range: 0.01 to 0.04 %

Air flow rate: 45.0 cfm.

Concentrations from 0.01 to 0.025 % corresponded to increasing removal efficiencies. The highest removal efficiency, 65 % at 0.03% concentration. Foaming problems developed after 0.025 % concentration.

Air flow rate: 81.0 cfm.

Removal efficiencies with this air flow were not very satisfactory, and pumping problems due to large foaming conditions appeared very early at 0.015 % surfactant concentration. Results are shown in Tables 77 through 88 and Figures 15 and 16.

The following surfactanst were used in the scrubbing sulfur dioxide process (Table3).

Table 3

Surfactant	:	Emulsynt 2400
Manufacturer	:	Van Dick & Co.
Ionic Character	:	Nonionic
Composition	:	Polyaxy alkylene oleate/laurate
Physical State	:	Liquid (light amber liquid)
Description	:	Emulsifier. Soluble in water, effective emulsifier over a wide pH range
Concentration (%)	:	100
Specific Gravity	:	1.030 to 1.055 (at 25°C)
Surfactant	:	Arsil 303-E
Manufacturer	:	Arjay Inc.
Ionic Character	:	Nonionic
Composition	:	Polydimethyl siloxane
Physical State	:	Liquid
Description	:	Used for highly alkaline and acid aqueous solutions
Concentration (%)	:	30
Specific Gravity	:	1.015 (at 25°C)
Surfactant	:	Mafo 13
Manufacturer	:	Mazer Chemicals
Ionic Character	:	Amphoteric
Composition	:	Potassium salt of complex N-stearyl
Physical State	:	Liquid (clear amber liquid)
Description	:	Water soluble detergent and surface active agent, compatible with strong acid and strong alkali

Table 3 (Continued)

solutions. Biodegradable.
Concentration (%) : 70
Specific Gravity : 1.010 - 1.025 (at 25 C)

Surfactant : Abex JKB
Manufacturer : Alcolac, Inc.
Ionic Character : Anionic
Composition : Anionic surfactant
Physical State : Liquid (clear liquid)
Description : Emulsifier for high-acid systems
Concentration (%) : 30
Specific Gravity : 1.01 (at 25°C)

Surfactant : Armohib - 31
Manufacturer : Armak Inc. Chem. Div.
Ionic Character : Cationic
Composition : Amine-based
Physical State : Liquid
Description : Acid, corrosion inhibitor. Used to reduce attack by sulfuric, sulfamic, acetic and phosphoric acids
Concentration : 100
Specific Gravity : 1.042 (at 25°C)

Surfactant : Cenetol HS
Manufacturer : Arkansas Co., Inc.
Ionic Character : Anionic
Composition : Sulfated fatty acid ester
Physical State : Liquid (amber liquid)
Description : Acid and alkali stable, low foaming, wetting,

Table 3 (Continued)

and penetrating agent

Concentration : 46

Specific Gravity : 1.05 (at 25°C)

Table 4

Venturi Scrubber Test

Surfactant: None.

Gas: Sulfur Dioxide.

Surfactant conc.: 0.0 %

Air flow: 45.0 cfm.

Liquid flow: 5.8 gpm.

SO_2 injected: 1650ppm.

Lab. Temperature: 23 °C.

Scrubbing Liquor Temp.: 15 °C.

Volume of Surfactant: 0 ml.

Volume of Solution: 82.25 gal.

Sampling Time* (min)	Temp. of air (°C) in	Temp. of air (°C) out	Airflow (ft/min)	SO_2 conc. in (ppm)	SO_2 conc. out (ppm)	SO_2 removal %
5	23	17	550	1500	850	43
5	23	17	500	1700	1105	35
5	22	17	500	1450	980	32
5	22	16	450	1400	980	30
5	22	16	550	1600	1120	30

*Samples taken at five minute intervals (total time running: 50 min.)

Average removal: 34.0 %.

Foaming conditions: --

Liquid to gas ratio (L/G): 0.017.

Table 5

Venturi Scrubber Test

Surfactant: None.

Gas: Sulfur Dioxide.

Surfactant conc.: 0.0 %

Air flow: 81.0 cfm.

Liquid flow: 8.4 gpm.

SO_2 injected: 1000 ppm.

Lab. Temperature: 23 °C.

Scrubbing Liquor Temp.: 15 °C.

Volume of Surfactant: 0 ml.

Volume of Solution: 82.25 gal.

Sampling Time* (min)	Temp. of air (°C) in	Temp. of air (°C) out	Airflow (ft/min)	SO_2 conc. in (ppm)	SO_2 conc. out (ppm)	SO_2 removal %
5	23	18	900	870	520	40
5	23	17	900	850	515	39
5	23	17	950	880	555	37
5	23	17	850	800	490	39
5	22	17	900	825	520	37

*Samples taken at five minute intervals (total time running: 50 min.)

Average removal: 38.4 %.

Foaming conditions: --

Liquid to gas ratio (L/G): 0.013.

Table 6

Test For Foaming Conditions

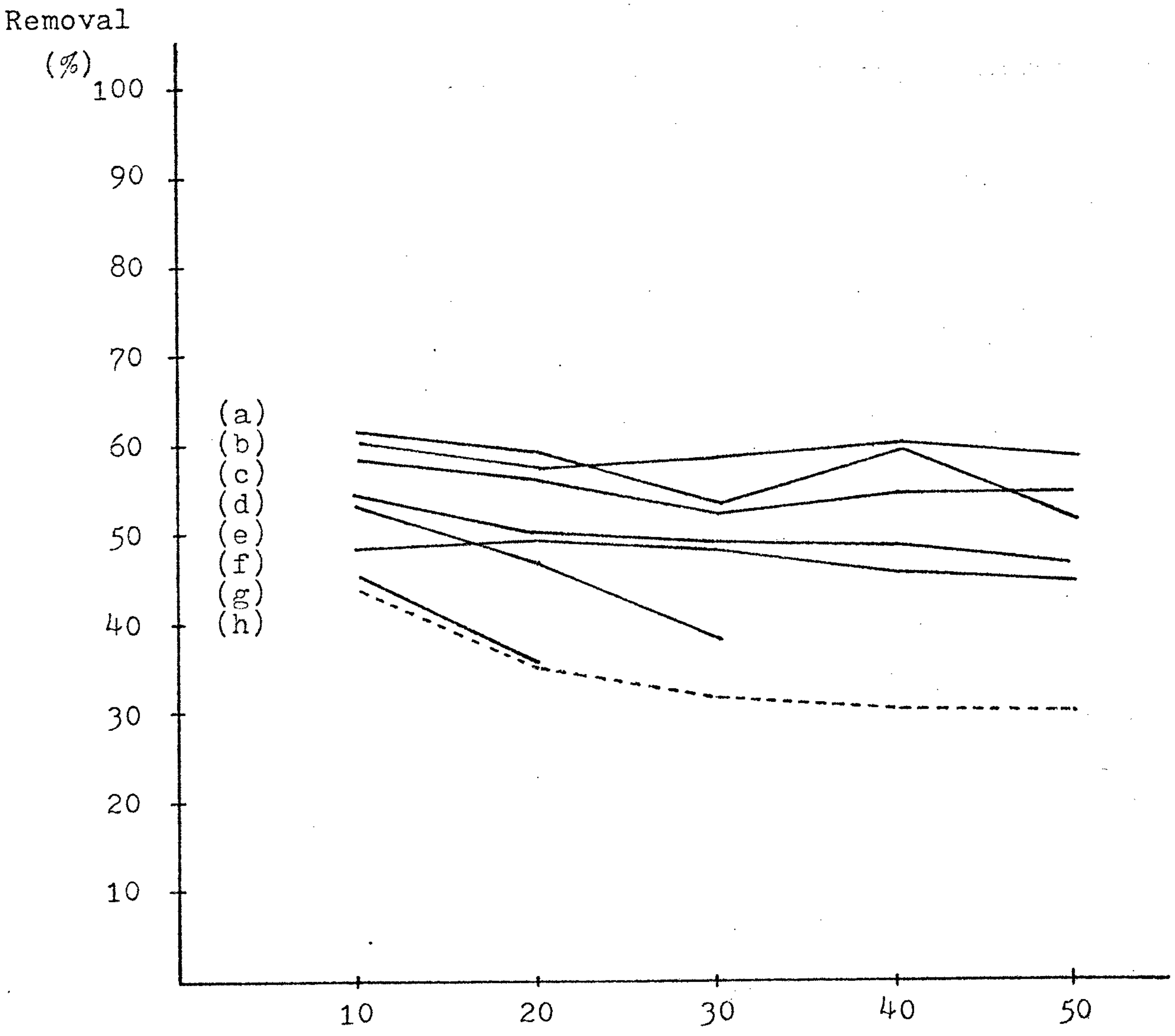
Surfactant	Liquid Flow Rate (gpm)	Surfactant Conc. (% by Vol.)	Foaming Conditions
Emulsynt 2400	5.2 8.4	>0.07 >0.06	Heavy Heavy
Arsyl 303-E	5.3 8.4	-- >1.0	--- Light
Mafo 13	8.3	>0.1	Heavy
Abex JKB	5.1 8.3	>0.03 >0.03	Heavy Heavy
Armohib 31	5.0 8.4	>0.02 >0.01	Heavy Heavy
Cenetol HS	5.2 8.3	>1.0 >1.0	Heavy Heavy

Figure(5)

Removal Efficiency (%) versus Time.

Surfactant: Emulsynt 2400.

Air Flow Rate: 45.0 cfm.



Curve	c*	Curve	c*
(a)	0.05	(e)	0.1
(b)	0.07	(f)	0.01
(c)	0.03	(g)	0.15
(d)	0.02	(h)	0.0

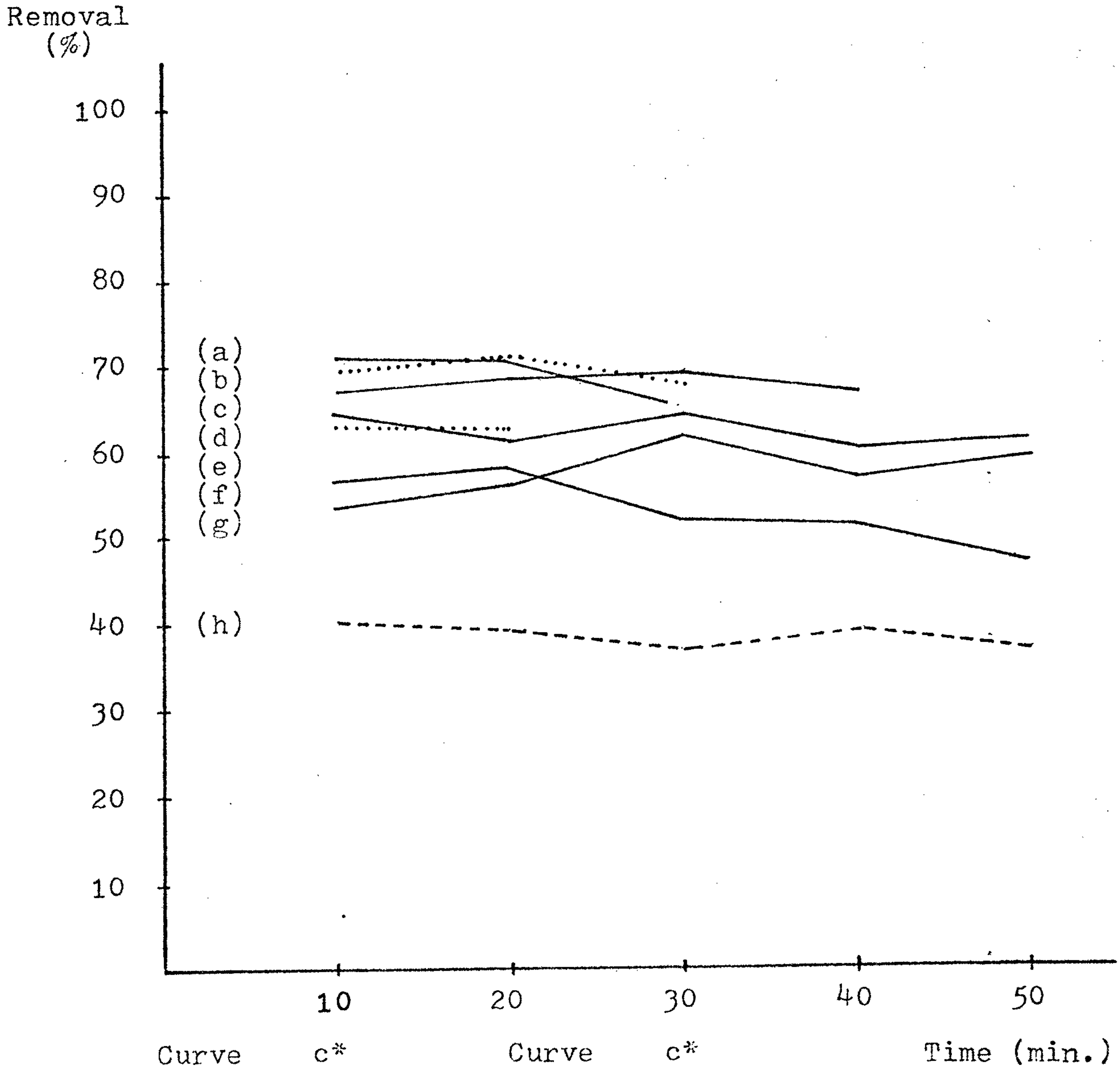
c* Surfactant concentration.

Figure (6)

Removal Efficiency (%) versus Time

Surfactant: Emulsynt 2400.

Air Flow Rate: 81.0 cfm.



Curve	c*	Curve	c*
(a)	0.05	(e)	0.15
(b)	0.1	(f)	0.02
(c)	0.07	(g)	0.01
(d)	0.03	(h)	0.0

c* Surfactant concentration.

Table 7

Venturi Scrubber Test

Surfactant: Emulsynt 2400　　Gas: Sulfur Dioxide.

Surfactant conc.: 0.01%　　Lab. Temperature: 23 °C.

Air flow: 45 cfm.　　Scrubbing Liquor Temp.: 15 °C.

Liquid flow: 5.8 gpm.　　Volume of Surfactant: 32 ml.

SO_2 injected: 1400 ppm.　　Volume of Solution: 82.25 gal.

Sampling Time* (min)	Temp. of air (°C) in	Temp. of air (°C) out	Airflow (ft/min)	SO_2 conc. in (ppm)	SO_2 conc. out (ppm)	SO_2 removal %
5	23	17	500	1300	670	48
5	23	17	500	1250	630	49
5	23	17	500	1380	720	48
5	23	17	500	1420	780	45
5	23	16	500	1410	790	44

*Samples taken at five minute intervals (total time running: 50 min.)

Average removal: 46.8%.

Foaming conditions: no foam.

Liquid to gas ratio (L/G): 0.017.

Table 8

Venturi Scrubber Test

Surfactant: Emulsynt 2400

Gas: Sulfur Dioxide.

Surfactant conc.: 0.01%

Air flow: 76.5 cfm.

Liquid flow: 6.8 gpm.

SO_2 injected: 1500 ppm.

Lab. Temperature: 23 °C.

Scrubbing Liquor Temp.: 15 °C.

Volume of Surfactant: 32 ml.

Volume of Solution: 82.25 gal.

Sampling Time* (min)	Temp. of air (°C) in	Temp. of air (°C) out	Airflow (ft/min)	SO_2 conc. in (ppm)	SO_2 conc. out (ppm)	SO_2 removal %
5	24	18	900	1450	615	57
5	23	18	850	1300	645	58
5	23	18	800	1580	752	52
5	23	17	850	1525	738	51
5	23	17	850	1400	780	44

*Samples taken at five minute intervals (total time running: 50 min.)

Average removal: 52.4%.

Foaming conditions: no foaming.

Liquid to gas ratio (L/G): 0.012.

Table 9

Venturi Scrubber Test

Surfactant: Emulsynt 2400 Gas: Sulfur Dioxide.

Surfactant conc.: 0.02%

Air flow: 45.6 cfm.

Liquid flow: gpm.

SO_2 injected: 1200 ppm.

Lab. Temperature: 23 °C.

Scrubbing Liquor Temp.: 15 °C.

Volume of Surfactant: 64 ml.

Volume of Solution: 82.25 gal.

Sampling Time* (min)	Temp. of air (°C) in	Temp. of air (°C) out	Airflow (ft/min)	SO_2 conc. in (ppm)	SO_2 conc. out (ppm)	SO_2 removal %
5	23	17	550	1100	500	54
5	23	17	530	920	458	50
5	22	17	520	1000	510	49
5	22	17	450	1285	653	49
5	22	16	500	1120	598	47

*Samples taken at five minute intervals (total time running: 50 min.)

Average removal: 49.8 %.

Foaming conditions: light.

Liquid to gas ratio (L/G): 0.016.

Table 10

Venturi Scrubber Test

Surfactant: Emulsynt 2400.

Gas: Sulfur Dioxide.

Surfactant conc.: 0.02 %

Air flow: 79.2 cfm.

Liquid flow: 7.5 gpm.

SO_2 injected: 1400 ppm.

Lab. Temperature: 23 °C.

Scrubbing Liquor Temp.: 15 °C.

Volume of Surfactant: 64 ml.

Volume of Solution: 82.25 gal.

Sampling Time* (min)	Temp. of air (°C) in	Temp. of air (°C) out	Airflow (ft/min)	SO_2 conc. in (ppm)	SO_2 conc. out (ppm)	SO_2 removal %
5	23	17	850	1350	615	53
5	23	17	850	1300	576	56
5	23	17	900	1250	475	62
5	22	17	900	1500	635	57
5	22	16	900	1420	585	59

*Samples taken at five minute intervals (total time running: 50 min.)

Average removal: 55.4 %.

Foaming conditions: light.

Liquid to gas ratio (L/G): 0.013.

Table 11

Venturi Scrubber Test

Surfactant: Emulsynt 2400.

Gas: Sulfur Dioxide.

Surfactant conc.: 0.03 %

Air flow: 43.2 cfm.

Liquid flow: 5.9 gpm.

SO_2 injected: 1350 ppm.

Lab. Temperature: 22 °C.

Scrubbing Liquor Temp.: 16°C.

Volume of Surfactant: 96 ml.

Volume of Solution: 82.25 gal.

Sampling Time* (min)	Temp. of air (°C) in	Temp. of air (°C) out	Airflow (ft/min)	SO_2 conc. in (ppm)	SO_2 conc. out (ppm)	SO_2 removal %
5	23	17	500	1280	538	58
5	23	17	500	1175	517	56
5	22	17	450	1300	618	52
5	22	16	450	1200	550	54
5	22	16	500	1100	500	54

*Samples taken at five minute intervals (total time running: 50 min.)

Average removal: 54.8 %.

Foaming conditions: light.

Liquid to gas ratio (L/G): 0.018.

Table 12

Venturi Scrubber Test

Surfactant: Emulsynt 2400. Gas: Sulfur Dioxide.

Surfactant conc.: 0.03 %
Air flow: 79.2 cfm.
Liquid flow: 7.8 gpm.
SO_2 injected: 1250 ppm.

Lab. Temperature: 23 °C.
Scrubbing Liquor Temp.: 15°C.
Volume of Surfactant: 96 ml.
Volume of Solution: 82.25 gal.

Sampling Time* (min)	Temp. of air (°C) in	Temp. of air (°C) out	Airflow (ft/min)	SO_2 conc. in (ppm)	SO_2 conc. out (ppm)	SO_2 removal %
5	23	17	900	1200	435	64
5	23	17	900	1100	428	61
5	23	17	900	1000	358	64
5	23	17	850	1350	535	60
5	23	16	850	1300	505	61

*Samples taken at five minute intervals (total time running: 50 min.)

Average removal: 62.0 %.

Foaming conditions: light.

Liquid to gas ratio (L/G): 0.013

Table 13

Venturi Scrubber Test

Surfactant: Emulsynt 2400 Gas: Sulfur Dioxide.

Surfactant conc.: 0.05 % Lab. Temperature: 22 °C.

Air flow: 52.7 cfm. Scrubbing Liquor Temp.: 16°C.

Liquid flow: 7.5 gpm. Volume of Surfactant: ml.

SO_2 injected: 1250 ppm. Volume of Solution: 82.25 gal.

Sampling Time* (min)	Temp. of air (°C) in	Temp. of air (°C) out	Airflow (ft/min)	SO_2 conc. in (ppm)	SO_2 conc. out (ppm)	SO_2 removal %
5	22	17	600	1150	452	61
5	22	17	580	1180	485	59
5	22	17	550	1300	615	53
5	22	16	600	1170	483	59
5	21	16	600	1280	620	51

*Samples taken at five minute intervals (total time running: 50 min.)

Average removal: 56.6%.

Foaming conditions: light.

Liquid to gas ratio (L/G): 0.018.

Table 14

Venturi Scrubber Test

Surfactant: Emulsynt 2400.	Gas: Sulfur Dioxide.
Surfactant conc.: 0.05%	Lab. Temperature: 22 °C.
Air flow: 81.0 cfm.	Scrubbing Liquor Temp.: 16 °C.
Liquid flow: 8.3 gpm.	Volume of Surfactant: 160 ml.
SO_2 injected: 1550 ppm.	Volume of Solution: 82.25 gal.

Sampling Time* (min)	Temp. of air (°C) in	Temp. of air (°C) out	Airflow (ft/min)	SO_2 conc. in (ppm)	SO_2 conc. out (ppm)	SO_2 removal %
5	23	17	900	1400	425	70
5	23	17	900	1300	385	70
5	23	17	900	1250	452	64
5	23	17	900	1300	*	*
5	23	17	900	1300	*	*

*Samples taken at five minute intervals (total time running: 50 min.)

Average removal: 68.0 %.

* pumping problems

Foaming conditions: heavy foaming.

Liquid to gas ratio (L/G): 0.014.

Table 15

Venturi Scrubber Test

Surfactant: Emulsynt 2400

Gas: Sulfur Dioxide.

Surfactant conc.: 0.07 %

Air flow: 45.0 cfm.

Liquid flow: 5.3 gpm.

SO_2 injected: 1350 ppm.

Lab. Temperature: 23 °C.

Scrubbing Liquor Temp.: 15 °C.

Volume of Surfactant: 224 ml.

Volume of Solution: 82.25 gal.

Sampling Time* (min)	Temp. of air (°C) in	Temp. of air (°C) out	Airflow (ft/min)	SO_2 conc. in (ppm)	SO_2 conc. out (ppm)	SO_2 removal %
5	22	15	500	1250	500	60.0
5	22	15	500	1300	560	56.9
5	22	15	500	1300	550	57.7
5	22	14	500	1400	574	59.0
5	22	14	500	1350	570	57.8

*Samples taken at five minute intervals (total time running: 50 min.)

Average removal: 58.3 %.

Foaming conditions: heavy foaming.

Liquid to gas ratio (L/G): 0.016.

Table 16

Venturi Scrubber Test

Surfactant: Emulsynt 2400.

Gas: Sulfur Dioxide.

Surfactant conc.: 0.07 %

Air flow: 81.0 cfm.

Liquid flow: 8.4 gpm.

SO_2 injected: 1500 ppm.

Lab. Temperature: 22 °C.

Scrubbing Liquor Temp.: 15 °C.

Volume of Surfactant: 224 ml.

Volume of Solution: 82.25 gal.

Sampling Time* (min)	Temp. of air (°C) in	Temp. of air (°C) out	Airflow (ft/min)	SO_2 conc. in (ppm)	SO_2 conc. out (ppm)	SO_2 removal %
5	22	14	900	1500	495	67.0
5	22	14	900	1450	464	68.0
5	22	14	900	1400	434	69.0
5	22	14	900	1450	479	66.9
5	22	14	900	*	*	*

*Samples taken at five minute intervals (total time running: 50 min.)

Average removal: 67.7 %.

* pumping problems.

Foaming conditions: very heavy foaming.

Liquid to gas ratio (L/G): 0.014.

Table 17

Venturi Scrubber Test

Surfactant: Emulsynt 2400

Gas: Sulfur Dioxide.

Surfactant conc.: 0.1%

Air flow: 43.2 cfm.

Liquid flow: 4.3 gpm.

SO_2 injected: 1600 ppm.

Lab. Temperature: 22 °C.

Scrubbing Liquor Temp.: 16 °C.

Volume of Surfactant: 320 ml.

Volume of Solution: 82.25 gal.

Sampling Time* (min)	Temp. of air (°C) in	Temp. of air (°C) out	Airflow (ft/min)	SO_2 conc. in (ppm)	SO_2 conc. out (ppm)	SO_2 removal %
5	22	17	500	1450	685	53
5	22	17	450	1350	710	47
5	22	17	450	1300	810	38
5	22	17	500	1500	* -	* -
5	22	17	500	1620	*	*

*Samples taken at five minute intervals (total time running: 50 min.)

Average removal: 46 %.

* pumping problems.

Foaming conditions: heavy.

Liquid to gas ratio (L/G): 0.013.

Table 18

Venturi Scrubber Test

Surfactant: Emulsynt 2400

Gas: Sulfur Dioxide.

Surfactant conc.: 0.1 %

Air flow: 79.0 cfm.

Liquid flow: 8.3 gpm.

SO_2 injected: 1400 ppm.

Lab. Temperature: 23 °C.

Scrubbing Liquor Temp.: 15 °C.

Volume of Surfactant: 320 ml.

Volume of Solution: 82.25 gal.

Sampling Time* (min)	Temp. of air (°C) in	Temp. of air (°C) out	Airflow (ft/min)	SO_2 conc. in (ppm)	SO_2 conc. out (ppm)	SO_2 removal %
5	22	16	950	1350	435	67.8
5	22	16	850	1450	435	70.0
5	22	16	800	1300	416	68.0
5	22	16	*	*	*	*
5	22	16	*	*	*	*

*Samples taken at five minute intervals (total time running: 50 min.)

Average removal: 68.6%.

* pumping problems.

Foaming conditions: very heavy foaming.

Liquid to gas ratio (L/G): 0.014.

Table 19

Venturi Scrubber Test

Surfactant: Emulsynt 2400.

Gas: Sulfur Dioxide.

Surfactant conc.: 0.15 %

Air flow: 45.9 cfm.

Liquid flow: 4.8 gpm.

SO_2 injected: 1380 ppm.

Lab. Temperature: 22 °C.

Scrubbing Liquor Temp.: 16 °C.

Volume of Surfactant: 480 ml.

Volume of Solution: 82.25 gal.

Sampling Time* (min)	Temp. of air (°C) in	Temp. of air (°C) out	Airflow (ft/min)	SO_2 conc. in (ppm)	SO_2 conc. out (ppm)	SO_2 removal %
5	23	18	500	1250	700	44.0
5	23	18	550	1200	780	35.0
5	23	17	500	1390	*	*
5	22	17	500	1420	*	*
5	22	17	550	1100	*	*

*Samples taken at five minute intervals (total time running: 50 min.)

Average removal: 39.5 %.

* pumpimg problems.

Foaming conditions: very heavy foaming.

Liquid to gas ratio (L/G): 0.014.

Table 20

Venturi Scrubber Test

Surfactant: Emulsynt 2400. Gas: Sulfur Dioxide.

Surfactant conc.: 0.15 %
Air flow: 72.0 cfm.
Liquid flow: 8.2 gpm.
SO_2 injected: 1200 ppm.

Lab. Temperature: 22 °C.
Scrubbing Liquor Temp.: 16 °C.
Volume of Surfactant: 480 ml.
Volume of Solution: 82.25 gal.

Sampling Time* (min)	Temp. of air (°C) in	Temp. of air (°C) out	Airflow (ft/min)	SO_2 conc. in (ppm)	SO_2 conc. out (ppm)	SO_2 removal %
5	22	15	900	1100	410	62.7
5	22	15	700	1000	380	62.0
5	22	15	*	*	*	*
5	22	15	*	*	*	*
5	22	15	*	*	*	*

*Samples taken at five minute intervals (total time running: 50 min.)

Average removal: 62.3 %.

* pumping problems.

Foaming conditions: very heavy foaming.

Liquid to gas ratio (L/G): 0.015.

Figure (7)

Removal Efficiency (%) versus Time

Surfactant: Arsil 303-E

Air Flow Rate: 45.0 cfm.

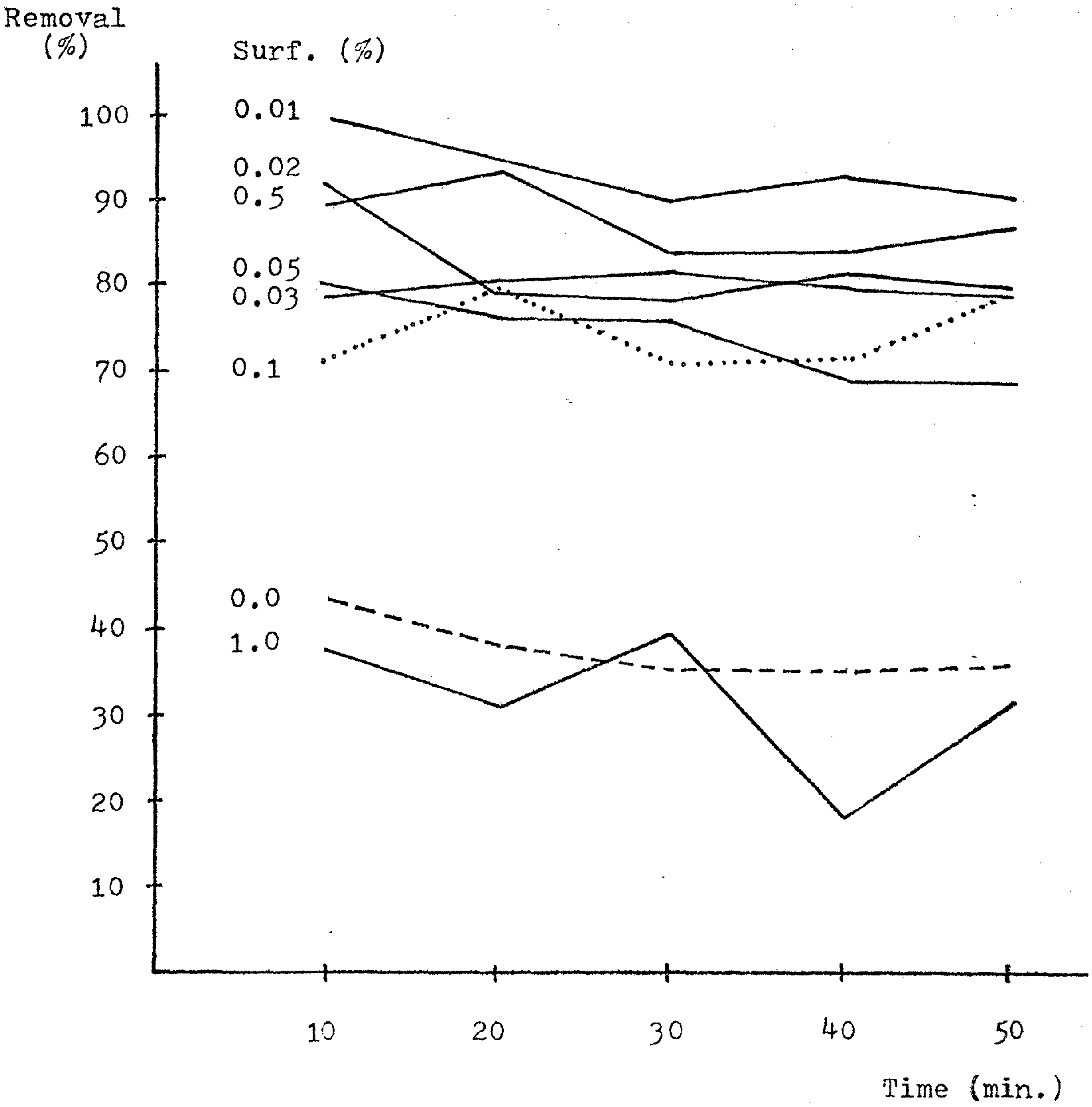


Figure (8)

Removal Efficiency (%) versus Time

Surfactant: Arsil 303-E

Air Flow Rate: 81.0 cfm.

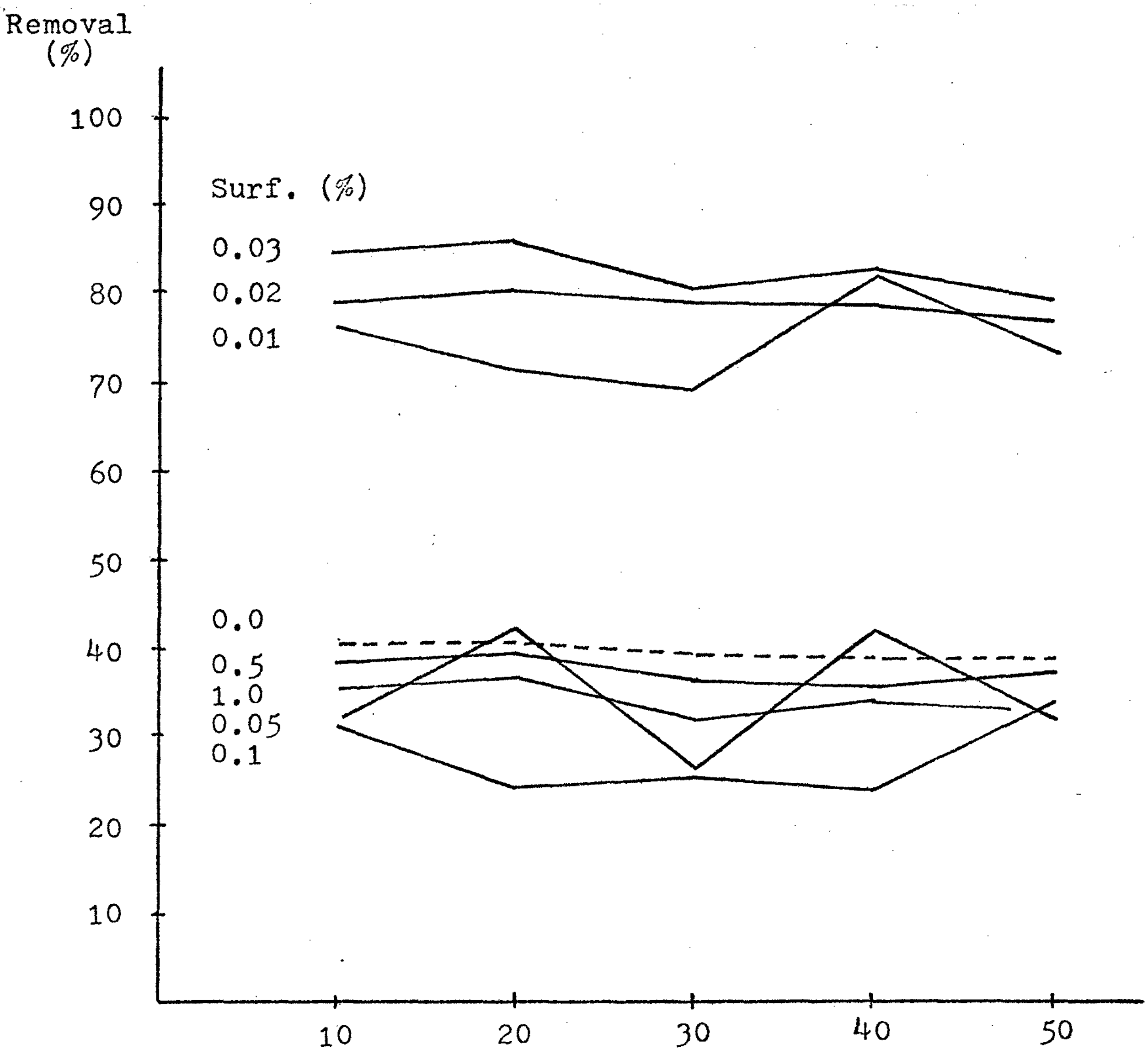


Table 21

Venturi Scrubber Test

Surfactant: Arsil 303-E.

Gas: Sulfur Dioxide.

Surfactant conc.: 0.01 %

Air flow: 45 cfm.

Liquid flow: 4.8 gpm.

SO_2 injected: 850 ppm.

Lab. Temperature: 22 °C.

Scrubbing Liquor Temp.: 15°C.

Volume of Surfactant: 32 ml.

Volume of Solution: 82.25 gal.

Sampling Time* (min)	Temp. of air (°C) in	Temp. of air (°C) out	Airflow (ft/min)	SO_2 conc. in (ppm)	SO_2 conc. out (ppm)	SO_2 removal %
5	22	14	500	448	243	99.4
5	22	14	500	274	17	94.0
5	22	14	500	1394	146	89.5
5	22	14	500	1095	83	92.4
5	22	14	500	647	68	89.5

*Samples taken at five minute intervals (total time running: 50 min.)

Average removal:92.96 %.

Foaming conditions: no foaming.

Liquid to gas ratio (L/G): 0.014.

Table 22

Venturi Scrubber Test

Surfactant: Arsil 303-E.	Gas: Sulfur Dioxide.
Surfactant conc.: 0.01 %	Lab. Temperature: 22 °C.
Air flow: 86.4 cfm.	Scrubbing Liquor Temp.: 16 °C.
Liquid flow: 8.4 gpm.	Volume of Surfactant: 32 ml.
SO_2 injected: 1100 ppm.	Volume of Solution: 82.25 gal.

Sampling Time* (min)	Temp. of air (°C) in	Temp. of air (°C) out	Airflow (ft/min)	SO_2 conc. in (ppm)	SO_2 conc. out (ppm)	SO_2 removal %
5	22	16	1000	942	218	76.9
5	22	16	950	893	254	71.5
5	22	16	950	847	265	68.7
5	22	16	950	1370	265	80.6
5	22	16	950	942	254	73.0

*Samples taken at five minute intervals (total time running: 50 min.)

Average removal: 74.14 %.

Foaming conditions: no foaming.

Liquid to gas ratio (L/G): 0.013.

Table 23

Venturi Scrubber Test

Surfactant: Arsil 303-E.

Gas: **Sulfur Dioxide.**

Surfactant conc.: 0.02%

Air flow: 45.0 cfm.

Liquid flow: 5.0 gpm.

SO_2 injected: 3500 ppm.

Lab. Temperature: 22 °C.

Scrubbing Liquor Temp.: 15 °C.

Volume of Surfactant: 64 ml.

Volume of Solution: 82.25 gal.

Sampling Time* (min)	Temp. of air (°C) in	Temp. of air (°C) out	Airflow (ft/min)	SO_2 conc. in (ppm)	SO_2 conc. out (ppm)	SO_2 removal %
5	22	14	500	3984	340	91.5
5	22	14	500	4606	972	79.0
5	22	14	500	4605	985	78.6
5	22	14	500	4360	835	80.8
5	22	14	500	3520	738	79.0

*Samples taken at five minute intervals (total time running: 50 min.)

Average removal: 81.78%.

Foaming conditions: no foaming.

Liquid to gas ratio (L/G): 0.015.

Table 24

Venturi Scrubber Test

Surfactant: Arsil 303-E.	Gas: Sulfur Dioxide.
Surfactant conc.: 0.02 %	Lab. Temperature: 22 °C.
Air flow: 81.0 cfm.	Scrubbing Liquor Temp.: 14 °C.
Liquid flow: 8.4 gpm.	Volume of Surfactant: 64 ml.
SO_2 injected: 1600 ppm.	Volume of Solution: 82.25 gal.

Sampling Time* (min)	Temp. of air (°C) in	Temp. of air (°C) out	Airflow (ft/min)	SO_2 conc. in (ppm)	SO_2 conc. out (ppm)	SO_2 removal %
5	22	16	900	1550	330	78.7
5	22	16	900	1450	290	80.0
5	22	16	900	1400	308	78.0
5	22	15	900	1600	340	78.7
5	22	15	900	1650	379	77.0

*Samples taken at five minute intervals (total time running: 50 min.)

Average removal: 78.5 %.

Foaming conditions: no foaming.

Liquid to gas ratio (L/G): 0.014.

Table 25

Venturi Scrubber Test

Surfactant: Arsil 303-E.

Gas: Sulfur Dioxide.

Surfactant conc.: 0.03 %

Air flow: 45.0 cfm.

Liquid flow: 5.3 gpm.

SO_2 injected: 1200 ppm.

Lab. Temperature: 22 °C.

Scrubbing Liquor Temp.: 15 °C.

Volume of Surfactant: 96 ml.

Volume of Solution: 82.25 gal.

Sampling Time* (min)	Temp. of air (°C) in	Temp. of air (°C) out	Airflow (ft/min)	SO_2 conc. in (ppm)	SO_2 conc. out (ppm)	SO_2 removal %
5	22	14	500	1100	242	78.0
5	22	14	500	1250	238	80.9
5	22	14	500	1300	234	82.0
5	22	14	500	1250	245	80.4
5	22	13	500	1200	250	79.2

*Samples taken at five minute intervals (total time running: 50 min.)

Average removal: 80.1 %.

Foaming conditions: no foaming.

Liquid to gas ratio (L/G): 0.016.

Table 26

Venturi Scrubber Test

Surfactant: Arsil 303-E.	Gas: Sulfur Dioxide.
Surfactant conc.: 0.03 %	Lab. Temperature: 21 °C.
Air flow: 81 cfm.	Scrubbing Liquor Temp.: 10 °C.
Liquid flow: 8.3 gpm.	Volume of Surfactant: 96 ml.
SO_2 injected: 1100 ppm.	Volume of Solution: 82.25 gal.

Sampling Time* (min)	Temp. of air (°C) in	Temp. of air (°C) out	Airflow (ft/min)	SO_2 conc. in (ppm)	SO_2 conc. out (ppm)	SO_2 removal %
5	20	15	900	1245	194	84.4
5	20	15	900	1494	207	86.2
5	20	15	900	1145	229	80.0
5	20	15	900	1105	198	82.1
5	20	15	900	970	205	78.8

*Samples taken at five minute intervals (total time running: 50 min.)

Average removal: 82.3 %.

Foaming conditions: no foaming.

Liquid to gas ratio (L/G): 0.014.

Table 27

Venturi Scrubber Test

Surfactant: Arsil 303-E. Gas: Sulfur Dioxide.

Surfactant conc.: 0.05% Lab. Temperature: 23 °C.

Air flow: 51.3 cfm. Scrubbing Liquor Temp.: 15 °C.

Liquid flow: 5.7 gpm. Volume of Surfactant: 160 ml.

SO_2 injected: 3300 ppm. Volume of Solution: 82.25 gal.

Sampling Time* (min)	Temp. of air (°C) in	Temp. of air (°C) out	Airflow (ft/min)	SO_2 conc. in (ppm)	SO_2 conc. out (ppm)	SO_2 removal %
5	22	16	550	3735	729	80.5
5	22	16	550	3610	850	76.4
5	22	16	600	3486	826	76.3
5	22	16	600	2614	826	68.4
5	22	16	550	2614	825	68.4

*Samples taken at five minute intervals (total time running: 50 min.)

Average removal: 74.0%.

Foaming conditions: no foaming.

Liquid to gas ratio (L/G): 0.015.

Table 28

Venturi Scrubber Test

Surfactant: Arsil 303-E.

Gas: Sulfur Dioxide.

Surfactant conc.: 0.05 %

Air flow: 81.0 cfm.

Liquid flow: 8.2 gpm.

SO_2 injected: 1300 ppm.

Lab. Temperature: 19 °C.

Scrubbing Liquor Temp.: 13 °C.

Volume of Surfactant: 160 ml.

Volume of Solution: 82.25 gal.

Sampling Time* (min)	Temp. of air (°C) in	Temp. of air (°C) out	Airflow (ft/min)	SO_2 conc. in (ppm)	SO_2 conc. out (ppm)	SO_2 removal %
5	19	15	900	985	670	31.9
5	19	15	900	1250	720	42.4
5	19	15	900	1100	810	26.4
5	19	15	900	1150	680	40.7
5	19	15	900	1050	720	31.4

*Samples taken at five minute intervals (total time running: 50 min.)

Average removal: 34.56%.

Foaming conditions: no foaming.

Liquid to gas ratio (L/G): 0.013.

Table 29

Venturi Scrubber Test

Surfactant: Arsil 303-E.　　Gas: Sulfur Dioxide.

Surfactant conc.: 0.1 %　　Lab. Temperature: 23 °C.

Air flow: 51.3 cfm.　　Scrubbing Liquor Temp.: 15 °C.

Liquid flow: 5.3 gpm.　　Volume of Surfactant: 320 ml.

SO_2 injected: 3200 ppm.　　Volume of Solution: 82.25 gal.

Sampling Time* (min)	Temp. of air (°C) in	Temp. of air (°C) out	Airflow (ft/min)	SO_2 conc. in (ppm)	SO_2 conc. out (ppm)	SO_2 removal %
5	22	15	550	2340	672	71.3
5	22	15	550	4108	826	80.0
5	22	15	550	3735	1093	70.7
5	22	15	600	4233	1215	71.3
5	22	14	600	4210	1480	79.2

*Samples taken at five minute intervals (total time running: 50 min.)

Average removal: 71.6 %.

Foaming conditions: no foaming.

Liquid to gas ratio (L/G): 0.014.

Table 30

Venturi Scrubber Test

Surfactant: Arsil 303-E.	Gas: Sulfur Dioxide.
Surfactant conc.: 0.1 %	Lab. Temperature: 19 °C.
Air flow: 81.0 cfm.	Scrubbing Liquor Temp.: 13 °C.
Liquid flow: 8.2 gpm.	Volume of Surfactant: 320 ml.
SO_2 injected: 1500 ppm.	Volume of Solution: 82.25 gal.

Sampling Time* (min)	Temp. of air (°C) in	Temp. of air (°C) out	Airflow (ft/min)	SO_2 conc. in (ppm)	SO_2 conc. out (ppm)	SO_2 removal %
5	18	14	900	1200	820	32.0
5	18	14	900	1150	875	23.9
5	18	14	900	1100	810	26.4
5	18	14	900	1220	920	24.6
5	18	14	900	1180	780	33.4

*Samples taken at five minute intervals (total time running: 50 min.)

Average removal:28.06 %.

Foaming conditions: no foaming.

Liquid to gas ratio (L/G): 0.014.

Table 31

Venturi Scrubber Test

Surfactant: Arsil 303- E

Gas: Sulfur Dioxide.

Surfactant conc.: 0.5 %

Air flow: 45.9 cfm.

Liquid flow: 6.1 gpm.

SO_2 injected: 1100 ppm.

Lab. Temperature: 22 °C.

Scrubbing Liquor Temp.: 12 °C.

Volume of Surfactant: 1600 ml.

Volume of Solution: 82.25 gal.

Sampling Time* (min)	Temp. of air (°C) in	Temp. of air (°C) out	Airflow (ft/min)	SO_2 conc. in (ppm)	SO_2 conc. out (ppm)	SO_2 removal %
5	22	16	500	942	98	89.6
5	22	16	500	893	67	92.5
5	22	16	500	1116	194	82.6
5	22	16	500	1116	194	82.6
5	22	16	550	744	103	86.1

*Samples taken at five minute intervals (total time running: 50 min.)

Average removal: 86.66 %.

Foaming conditions: no foaming.

Liquid to gas ratio (L/G): 0.018.

Table 32

Venturi Scrubber Test

Surfactant: Arsil 303-E.

Gas: Sulfur Dioxide.

Surfactant conc.: 0.5 %

Air flow: 81.0 cfm.

Liquid flow: 8.3 gpm.

SO_2 injected: 1600 ppm.

Lab. Temperature: 22 °C.

Scrubbing Liquor Temp.: 13 °C.

Volume of Surfactant: 1600 ml.

Volume of Solution: 82.25 gal.

Sampling Time* (min)	Temp. of air (°C) in	Temp. of air (°C) out	Airflow (ft/min)	SO_2 conc. in (ppm)	SO_2 conc. out (ppm)	SO_2 removal %
5	21	15	900	1400	868	38.0
5	21	15	900	1480	903	38.9
5	21	15	900	1569	997	36.4
5	21	14	900	1500	975	35.0
5	21	14	900	1630	1025	37.2

*Samples taken at five minute intervals (total time running: 50 min.)

Average removal: 37.1 %.

Foaming conditions: no foaming.

Liquid to gas ratio (L/G): 0.014.

Table 33

Venturi Scrubber Test

Surfactant: Arsil 303-E.	Gas: Sulfur Dioxide.
Surfactant conc.: 1.0 %	Lab. Temperature: 22 °C.
Air flow: 46.8 cfm.	Scrubbing Liquor Temp.: 12 °C.
Liquid flow: 5.3 gpm.	Volume of Surfactant: 3200 ml.
SO_2 injected: 980 ppm.	Volume of Solution: 82.25 gal.

Sampling Time* (min)	Temp. of air (°C) in	Temp. of air (°C) out	Airflow (ft/min)	SO_2 conc. in (ppm)	SO_2 conc. out (ppm)	SO_2 removal %
5	22	16	500	1389	864	37.8
5	22	16	550	1339	912	31.9
5	22	16	550	1339	816	39.0
5	22	16	500	1116	912	18.3
5	22	16	500	2381	1632	31.4

*Samples taken at five minute intervals (total time running: 50 min.)

Average removal: 31.68%.

Foaming conditions: no foaming.

Liquid to gas ratio (L/G): 0.015.

Table 34

Venturi Scrubber Test

Surfactant: Arsil 303-E.

Gas: Sulfur Dioxide.

Surfactant conc.: 1.0 %

Air flow: 81.0 cfm.

Liquid flow: 8.4 gpm.

SO_2 injected: 1800 ppm.

Lab. Temperature: 22 °C.

Scrubbing Liquor Temp.: 13 °C.

Volume of Surfactant: 3200 ml.

Volume of Solution: 82.25 gal.

Sampling Time* (min)	Temp. of air (°C) in	Temp. of air (°C) out	Airflow (ft/min)	SO_2 conc. in (ppm)	SO_2 conc. out (ppm)	SO_2 removal %
5	22	14	900	1700	1105	35.0
5	22	14	900	1750	1110	36.6
5	22	14	900	1800	1190	33.9
5	22	14	900	1800	1180	34.4
5	22	14	900	1850	1240	32.9

*Samples taken at five minute intervals (total time running: 50 min.)

Average removal: 34.6 %.

Foaming conditions: no foaming.

Liquid to gas ratio (L/G): 0.014.

Figure (9)

Removal Efficiency (%) versus Time

Surfactant: Mafo 13

Air Flow Rate: 45.0 cfm.

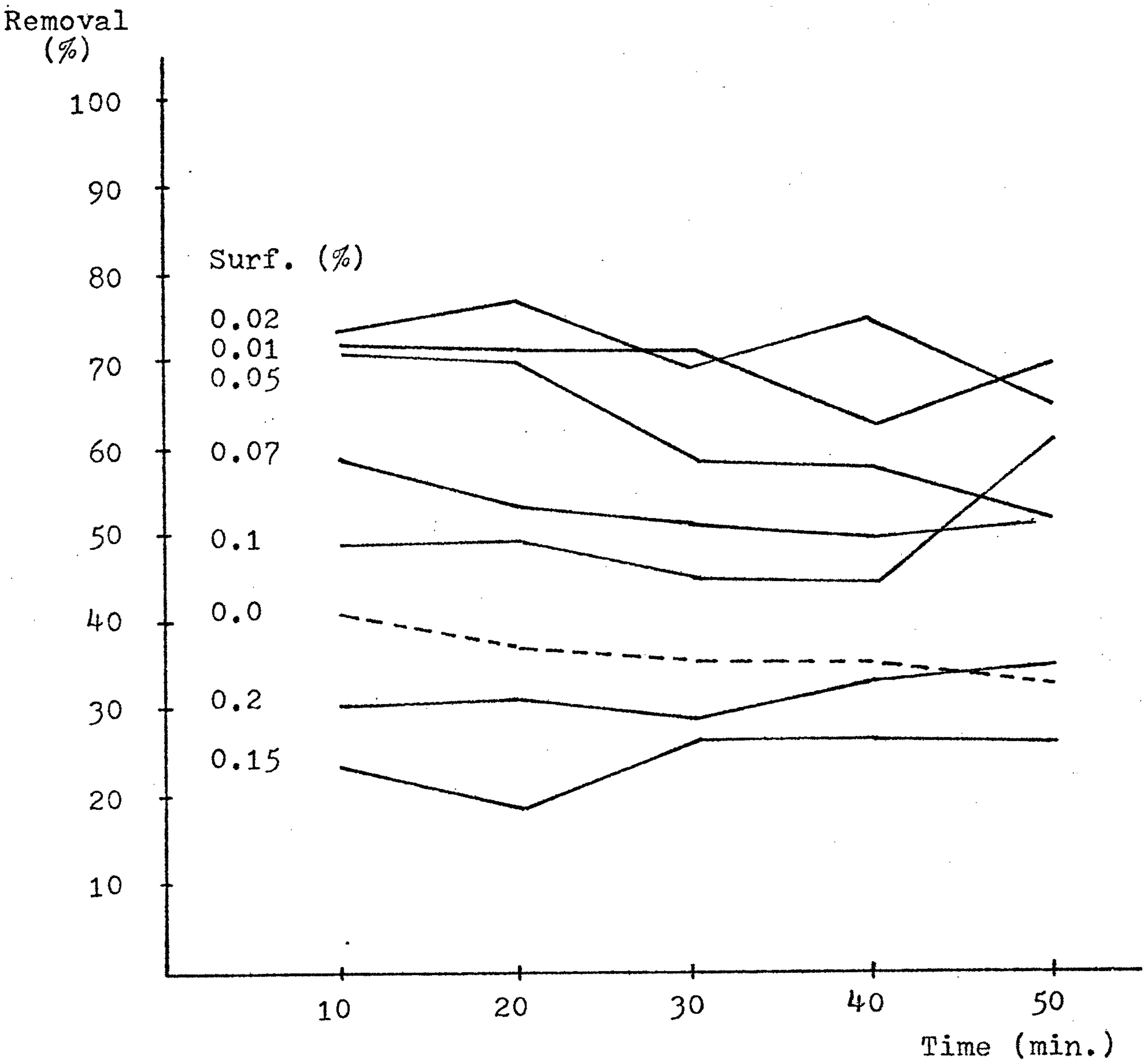


Figure (10)

Removal Efficiency (%) versus Time

Surfactant: Mafo 13

Air Flow Rate: 81.0 cfm.

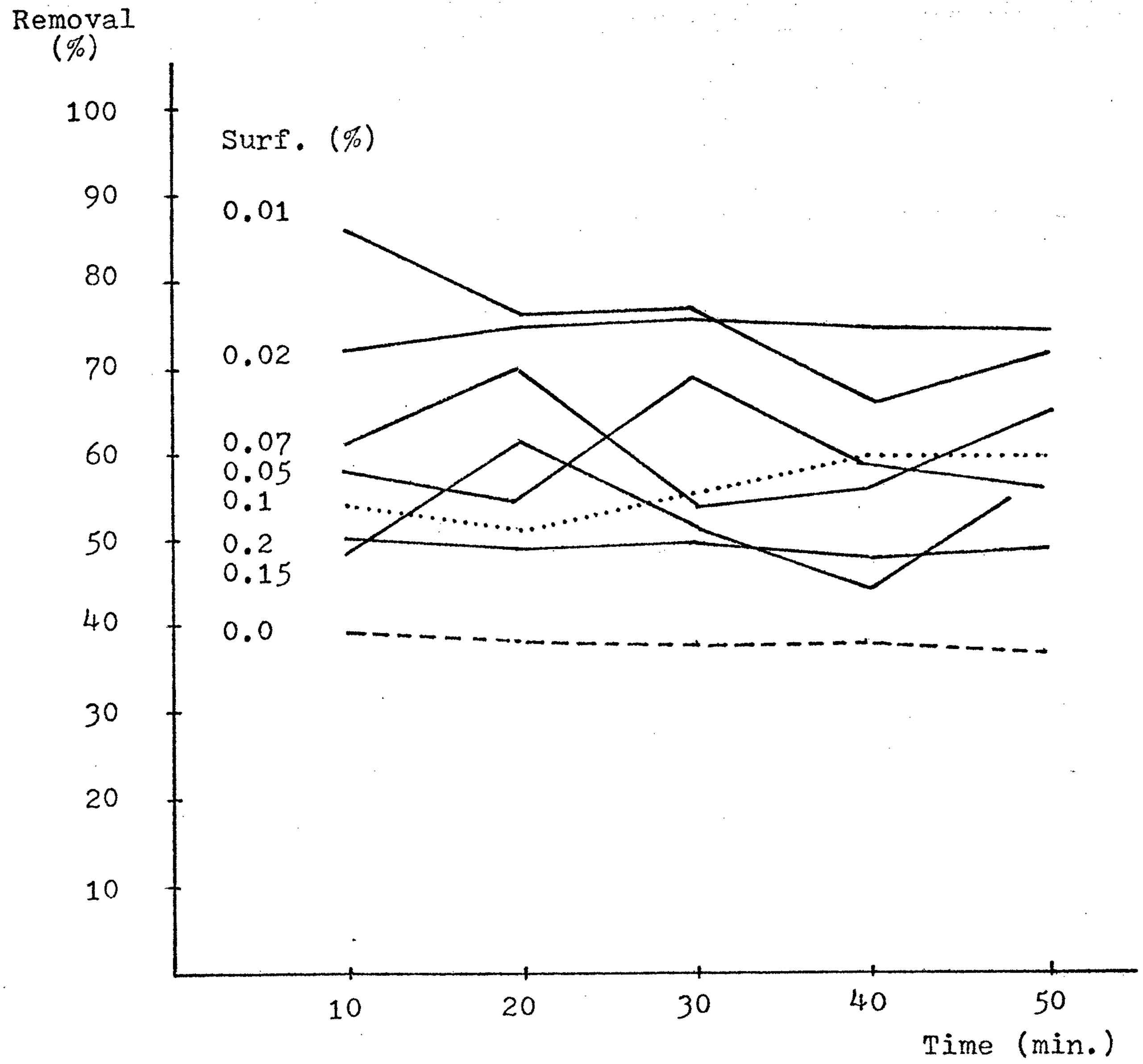


Table 35

Venturi Scrubber Test

Surfactant: Mafo 13

Gas: Sulfur Dioxide.

Surfactant conc.: 0.01 %

Air flow: 45.0 cfm.

Liquid flow: 5.3 gpm.

SO_2 injected: 1400 ppm.

Lab. Temperature: 19 °C.

Scrubbing Liquor Temp.: 13 °C.

Volume of Surfactant: 32 ml.

Volume of Solution: 82.25 gal.

Sampling Time* (min)	Temp. of air (°C) in	Temp. of air (°C) out	Airflow (ft/min)	SO_2 conc. in (ppm)	SO_2 conc. out (ppm)	SO_2 removal %
5	22	15	500	1500	420	72.0
5	22	15	500	1350	395	70.7
5	22	15	550	1280	380	70.3
5	22	15	450	1120	420	62.5
5	22	15	500	1300	400	69.2

*Samples taken at five minute intervals (total time running: 50 min.)

Average removal. 68.94%.

Foaming conditions: no foaming.

Liquid to gas ratio (L/G): 0.016.

Table 36

Venturi Scrubber Test

Surfactant: Mafo 13.	Gas: Sulfur Dioxide.
Surfactant conc.: 0.01%	Lab. Temperature: 22 °C.
Air flow: 81.9 cfm.	Scrubbing Liquor Temp.: 12 °C.
Liquid flow: 8.45 gpm.	Volume of Surfactant: 32 ml.
SO_2 injected: 500 ppm.	Volume of Solution: 82.25 gal.

Sampling Time* (min)	Temp. of air (°C) in	Temp. of air (°C) out	Airflow (ft/min)	SO_2 conc. in (ppm)	SO_2 conc. out (ppm)	SO_2 removal %
5	22	16	900	386	54	86.0
5	22	16	950	299	70	76.6
5	22	16	900	448	103	77.0
5	22	15	900	398	134	66.3
5	22	15	900	349	99	71.6

*Samples taken at five minute intervals (total time running: 50 min.)

Average removal: 75.5%.

Foaming conditions: no foaming.

Liquid to gas ratio (L/G): 0.014.

Table 37

Venturi Scrubber Test

Surfactant: Mafo 13.

Gas: Sulfur Dioxide.

Surfactant conc.: 0.02 %

Air flow: 45.0 cfm.

Liquid flow: 5.2 gpm.

SO_2 injected: 1400 ppm.

Lab. Temperature: 21 °C.

Scrubbing Liquor Temp.: 16°C.

Volume of Surfactant: 64 ml.

Volume of Solution: 82.25 gal.

Sampling Time* (min)	Temp. of air (°C) in	Temp. of air (°C) out	Airflow (ft/min)	SO_2 conc. in (ppm)	SO_2 conc. out (ppm)	SO_2 removal %
5	22	15	500	1350	370	72.6
5	22	15	500	1400	325	76.8
5	22	15	500	1500	475	68.3
5	22	14	500	1280	325	74.5
5	22	14	500	1360	485	64.3

*Samples taken at five minute intervals (total time running: 50 min.)

Average removal: 71.32%.

Foaming conditions: no foaming.

Liquid to gas ratio (L/G): 0.015

Table 38

Venturi Scrubber Test

Surfactant: Mafo 13.

Gas: Sulfur Dioxide.

Surfactant conc.: 0.02 %

Air flow: 81.0 cfm.

Liquid flow: 8.25 gpm.

SO_2 injected: 2000 ppm.

Lab. Temperature: 22 °C.

Scrubbing Liquor Temp.: 10 °C.

Volume of Surfactant: 64 ml.

Volume of Solution: 82.25 gal.

Sampling Time* (min)	Temp. of air (°C) in	Temp. of air (°C) out	Airflow (ft/min)	SO_2 conc. in (ppm)	SO_2 conc. out (ppm)	SO_2 removal %
5	22	15	900	1400	392	72.0
5	22	15	900	1145	287	74.9
5	22	15	900	1320	320	75.7
5	22	14	900	1444	391	72.9
5	22	14	900	1320	358	72.9

*Samples taken at five minute intervals (total time running: 50 min.)

Average removal: 73.7 %.

Foaming conditions: no foaming.

Liquid to gas ratio (L/G): 0.013.

Table 39

Venturi Scrubber Test

Surfactant: Mafo 13.

Gas: Sulfur Dioxide.

Surfactant conc.: 0.05 %

Air flow: 45.0 cfm.

Liquid flow: 5.4 gpm.

SO_2 injected: 1400 ppm.

Lab. Temperature: 20 °C.

Scrubbing Liquor Temp.: 16 °C.

Volume of Surfactant: 160 ml.

Volume of Solution: 82.25 gal.

Sampling Time* (min)	Temp. of air (°C) in	Temp. of air (°C) out	Airflow (ft/min)	SO_2 conc. in (ppm)	SO_2 conc. out (ppm)	SO_2 removal %
5	22	15	500	1600	462	71.1
5	22	15	500	1580	475	69.9
5	22	15	500	1500	632	57.9
5	22	14	500	1500	641	57.3
5	22	14	500	1480	635	51.1

*Samples taken at five minute intervals (total time running: 50 min.)

Average removal: 61.5 %.

Foaming conditions: no foaming.

Liquid to gas ratio (L/G): 0.016.

Table 40

Venturi Scrubber Test

Surfactant: Mafo 13.	Gas: Sulfur Dioxide.
Surfactant conc.: 0.05 %	Lab. Temperature: 22 °C.
Air flow: 75.6 cfm.	Scrubbing Liquor Temp.: 10 °C.
Liquid flow: 8.2 gpm.	Volume of Surfactant: 160 ml.
SO_2 injected: 2200 ppm.	Volume of Solution: 82.25 gal.

Sampling Time* (min)	Temp. of air (°C) in	Temp. of air (°C) out	Airflow (ft/min)	SO_2 conc. in (ppm)	SO_2 conc. out (ppm)	SO_2 removal %
5	19	14	900	3735	1584	57.6
5	19	14	900	3486	1584	54.5
5	19	13	850	4233	1344	68.2
5	19	13	800	2739	1125	58.9
5	19	13	750	2490	1085	56.4

*Samples taken at five minute intervals (total time running: 50 min.)

Average removal: 59.1 %.

Foaming conditions: light foaming.

Liquid to gas ratio (L/G): 0.014.

Table 41

Venturi Scrubber Test

Surfactant: Mafo 13.

Gas: Sulfur Dioxide.

Surfactant conc.: 0.07 %

Air flow: 45.0 cfm.

Liquid flow: 5.6 gpm.

SO_2 injected: 1550 ppm.

Lab. Temperature: 21 °C.

Scrubbing Liquor Temp.: 16 °C.

Volume of Surfactant: 224 ml.

Volume of Solution: 82.25 gal.

Sampling Time* (min)	Temp. of air (°C) in	Temp. of air (°C) out	Airflow (ft/min)	SO_2 conc. in (ppm)	SO_2 conc. out (ppm)	SO_2 removal %
5	22	15	500	1500	625	58.3
5	22	15	500	1480	683	53.8
5	22	15	500	1350	652	51.7
5	22	15	500	1420	722	49.2
5	22	15	500	1450	698	51.9

*Samples taken at five minute intervals (total time running: 50 min.)

Average removal: 52.98%.

Foaming conditions: no foaming.

Liquid to gas ratio (L/G): 0.016.

Table 42

Venturi Scrubber Test

Surfactant: Mafo 13.

Gas: Sulfur Dioxide.

Surfactant conc.: 0.07 %

Air flow: 77.4 cfm.

Liquid flow: 8.15 gpm.

SO_2 injected: 1100 ppm.

Lab. Temperature: 22 °C.

Scrubbing Liquor Temp.: 10 °C.

Volume of Surfactant: 224 ml.

Volume of Solution: 82.25 gal.

Sampling Time* (min)	Temp. of air (°C) in	Temp. of air (°C) out	Airflow (ft/min)	SO_2 conc. in (ppm)	SO_2 conc. out (ppm)	SO_2 removal %
5	22	16	900	1320	517	60.8
5	22	16	850	1280	385	69.9
5	22	15	850	1500	693	53.8
5	22	15	850	1120	485	56.7
5	22	15	850	1230	432	64.9

*Samples taken at five minute intervals (total time running: 50 min.)

Average removal: 61.2 %.

Foaming conditions: heavy foaming.

Liquid to gas ratio (L/G): 0.014.

Table 43

Venturi Scrubber Test

Surfactant: Mafo 13.

Gas: Sulfur Dioxide.

Surfactant conc.: 0.10 %

Air flow: 45.0 cfm.

Liquid flow: 5.35 gpm.

SO_2 injected: 1300 ppm.

Lab. Temperature: 21 °C.

Scrubbing Liquor Temp.: 16 °C.

Volume of Surfactant: 310 ml.

Volume of Solution: 82.25 gal.

Sampling Time* (min)	Temp. of air (°C) in	Temp. of air (°C) out	Airflow (ft/min)	SO_2 conc. in (ppm)	SO_2 conc. out (ppm)	SO_2 removal %
5	22	15	500	1120	580	48.2
5	22	15	500	1250	635	49.2
5	22	15	500	1300	715	45.0
5	22	14	500	1290	725	43.8
5	22	14	500	1320	525	60.2

*Samples taken at five minute intervals (total time running: 50 min.)

Average removal: 49.3 %.

Foaming conditions: no foaming.

Liquid to gas ratio (L/G): 0.016.

Table 44

Venturi Scrubber Test

Surfactant: Mafo 13.

Gas: Sulfur Dioxide.

Surfactant conc.: 0.1 %

Air flow: 78.3 cfm.

Liquid flow: 8.25 gpm.

SO_2 injected: 1200 ppm.

Lab. Temperature: 21 °C.

Scrubbing Liquor Temp.: 12°C.

Volume of Surfactant: 320 ml.

Volume of Solution: 82.25 gal.

Sampling Time* (min)	Temp. of air (°C) in	Temp. of air (°C) out	Airflow (ft/min)	SO_2 conc. in (ppm)	SO_2 conc. out (ppm)	SO_2 removal %
5	22	16	900	1350	628	53.5
5	22	16	900	1280	615	51.9
5	22	16	850	1300	583	55.1
5	22	15	850	1100	453	58.8
5	22	15	850	1050	421	59.9

*Samples taken at five minute intervals (total time running: 50 min.)

Average removal: 58.8 %.

Foaming conditions: heavy foaming.

Liquid to gas ratio (L/G): 0.014.

Table 45

Venturi Scrubber Test

Surfactant: Mafo 13.

Gas: Sulfur Dioxide.

Surfactant conc.: 0.15 %

Air flow: 45.0 cfm.

Liquid flow: 5.2 gpm.

SO_2 injected: 950 ppm.

Lab. Temperature: 22 °C.

Scrubbing Liquor Temp.: 14°C.

Volume of Surfactant: 480 ml.

Volume of Solution: 82.25 gal.

Sampling Time* (min)	Temp. of air (°C) in	Temp. of air (°C) out	Airflow (ft/min)	SO_2 conc. in (ppm)	SO_2 conc. out (ppm)	SO_2 removal %
5	20	14	550	885	670	24.3
5	20	14	550	920	740	19.5
5	20	14	500	1050	765	27.1
5	20	14	450	990	720	27.3
5	19	13	450	950	695	26.8

*Samples taken at five minute intervals (total time running: 50 min.)

Average removal: 25.0%.

Foaming conditions: light foaming.

Liquid to gas ratio (L/G): 0.015.

Table 46

Venturi Scrubber Test

Surfactant: Mafo 13. Gas: Sulfur Dioxide.

Surfactant conc.: 0.15%

Air flow: 82.8 cfm.

Liquid flow: 8.45 gpm.

SO_2 injected: 1500 ppm.

Lab. Temperature: 22 °C.

Scrubbing Liquor Temp.: 12 °C.

Volume of Surfactant: 480 ml.

Volume of Solution: 82.25 gal.

Sampling Time* (min)	Temp. of air (°C) in	Temp. of air (°C) out	Airflow (ft/min)	SO_2 conc. in (ppm)	SO_2 conc. out (ppm)	SO_2 removal %
5	22	15	950	1650	863	47.7
5	22	15	950	1700	652	61.6
5	22	15	900	1720	824	52.1
5	22	15	900	1510	852	43.6
5	22	15	900	1480	631	57.4

*Samples taken at five minute intervals (total time running: 50 min.)

Average removal: 52.5 %.

Foaming conditions: heavy foaming.

Liquid to gas ratio (L/G): 0.014.

Table 47

Venturi Scrubber Test

Surfactant: Mafo 13.

Gas: Sulfur Dioxide.

Surfactant conc.: 0.2 %

Air flow: 45.0 cfm.

Liquid flow: 5.3 gpm.

SO_2 injected: 2000 ppm.

Lab. Temperature: 21 °C.

Scrubbing Liquor Temp.: 13 °C.

Volume of Surfactant: 640 ml.

Volume of Solution: 82.25 gal.

Sampling Time* (min)	Temp. of air (°C) in	Temp. of air (°C) out	Airflow (ft/min)	SO_2 conc. in (ppm)	SO_2 conc. out (ppm)	SO_2 removal %
5	22	16	500	1950	1345	31.0
5	22	16	500	1900	1290	32.0
5	22	15	500	1900	1350	28.9
5	22	15	500	1850	1240	32.9
5	22	15	500	2000	1300	35.0

*Samples taken at five minute intervals (total time running: 50 min.)

Average removal: 31.9 %.

Foaming conditions: light foaming.

Liquid to gas ratio (L/G): 0.016.

Table 48

Venturi Scrubber Test

Surfactant: Mafo 13.

Gas: Sulfur Dioxide.

Surfactant conc.: 0.2 %

Air flow: 81.0 cfm.

Liquid flow: 8.35 gpm.

SO_2 injected: 2000 ppm.

Lab. Temperature: 21 °C.

Scrubbing Liquor Temp.: 13 °C.

Volume of Surfactant: 640 ml.

Volume of Solution: 82.25 gal.

Sampling Time* (min)	Temp. of air (°C) in	Temp. of air (°C) out	Airflow (ft/min)	SO_2 conc. in (ppm)	SO_2 conc. out (ppm)	SO_2 removal %
5	22	15	900	2100	1050	50.0
5	22	15	900	2000	1040	48.0
5	22	14	900	1950	995	48.9
5	22	14	900	1800	954	47.0
5	21	14	900	1850	965	47.8

*Samples taken at five minute intervals (total time running: 50 min.)

Average removal: 48.3 %.

Foaming conditions: very heavy foaming.

Liquid to gas ratio (L/G): 0.014.

Figure 11

Removal Efficiency (%) versus Time

Surfactant: Abex JKB

Air Flow Rate: 45.0 cfm.

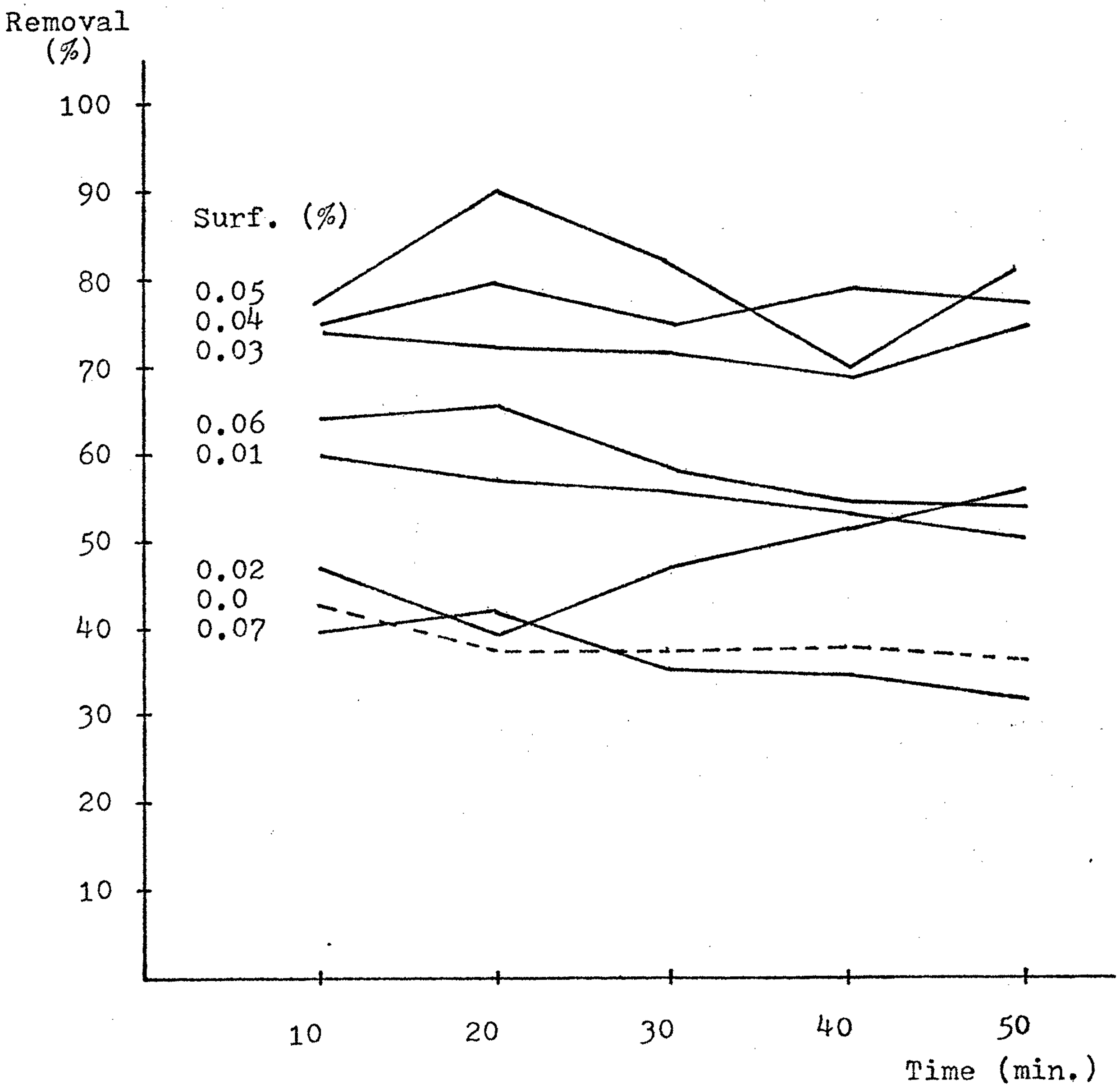


Figure 12

Removal Efficiency (%) versus Time

Surfactant: Abex JKB

Air Flow Rate: 81.0 cfm.

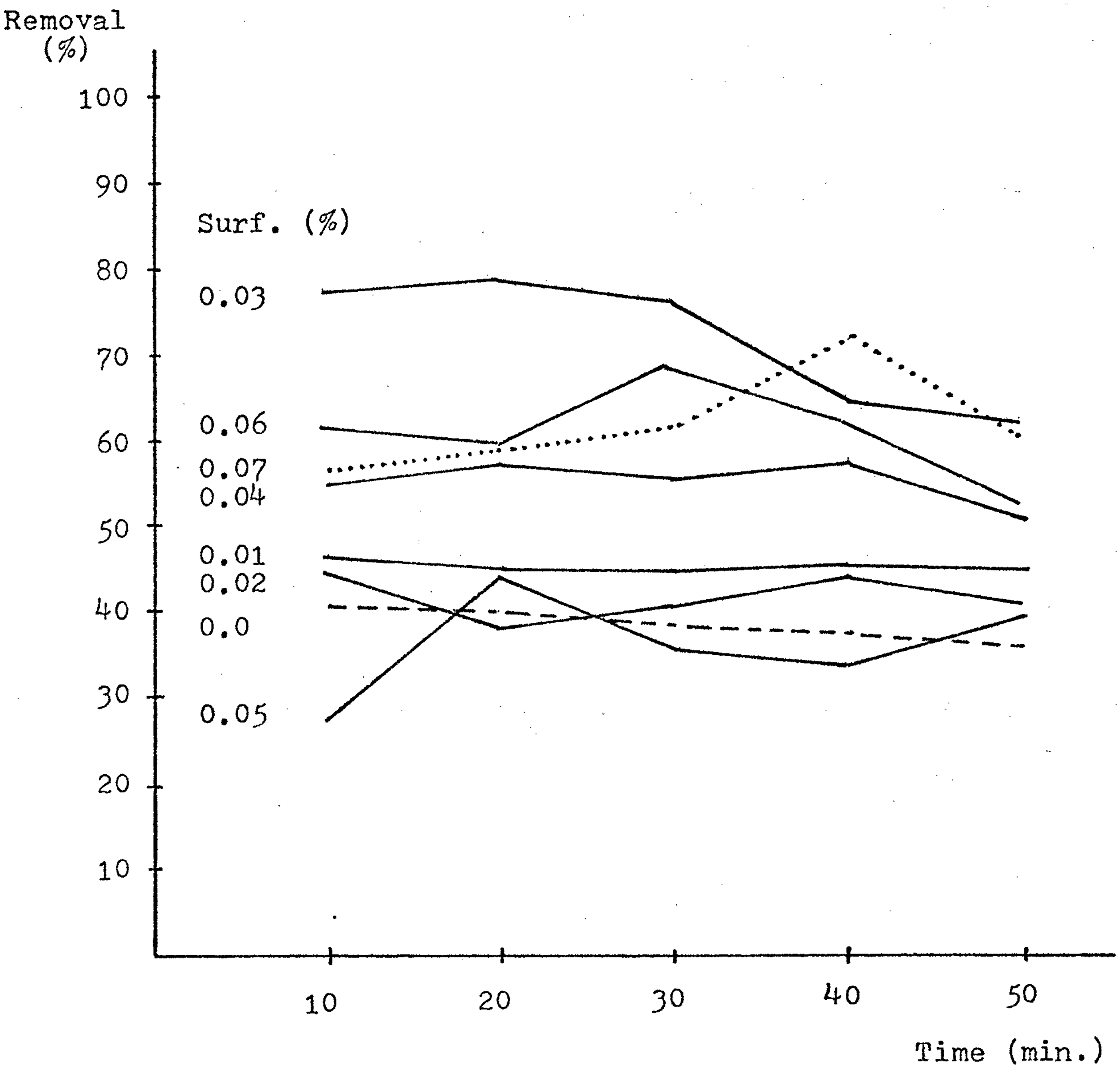


Table 49

Venturi Scrubber Test

Surfactant: Abex JKB. Gas: Sulfur Dioxide.

Surfactant conc.:0.01 %

Air flow: 45.0 cfm.

Liquid flow: 5.3 gpm.

SO_2 injected: 1400 ppm.

Lab. Temperature: 22 °C.

Scrubbing Liquor Temp.: 13 °C.

Volume of Surfactant: 32 ml.

Volume of Solution: 82.25 gal.

Sampling Time* (min)	Temp. of air (°C) in	Temp. of air (°C) out	Airflow (ft/min)	SO_2 conc. in (ppm)	SO_2 conc. out (ppm)	SO_2 removal %
5	22	14	500	1700	685	59.7
5	22	14	500	1650	710	56.9
5	22	14	500	1600	715	55.3
5	22	14	500	1750	835	52.3
5	22	14	500	1750	875	50.0

*Samples taken at five minute intervals (total time running: 50 min.)

Average removal: 54,8 %.

Foaming conditions: no foaming.

Liquid to gas ratio (L/G): 0.017.

Table 50

Venturi Scrubber Test

Surfactant: Abex JKB.	Gas: Sulfur Dioxide.
Surfactant conc.: 0.01 %	Lab. Temperature: 22 °C.
Air flow: 81.0 cfm.	Scrubbing Liquor Temp.: 14 °C.
Liquid flow: 8.3 gpm.	Volume of Surfactant: 32 ml.
SO_2 injected: 1500 ppm.	Volume of Solution: 82.25 gal.

Sampling Time* (min)	Temp. of air (°C) in	Temp. of air (°C) out	Airflow (ft/min)	SO_2 conc. in (ppm)	SO_2 conc. out (ppm)	SO_2 removal %
5	22	14	900	1400	750	46.4
5	21	14	900	1350	745	44.8
5	21	13	900	1300	730	43.8
5	21	13	900	1450	798	44.9
5	21	13	900	1400	785	43.9

*Samples taken at five minute intervals (total time running: 50 min.)

Average removal: 44.8 %.

Foaming conditions: no foaming.

Liquid to gas ratio (L/G): 0.014.

Table 51

Venturi Scrubber Test

Surfactant: Abex JKB.

Gas: Sulfur Dioxide.

Surfactant conc.: 0.02%

Air flow: 46.8 cfm.

Liquid flow: 4.37 gpm.

SO_2 injected: 2900 ppm.

Lab. Temperature: 20 °C.

Scrubbing Liquor Temp.: 10 °C.

Volume of Surfactant: 64 ml.

Volume of Solution: 82.25 gal.

Sampling Time* (min)	Temp. of air (°C) in	Temp. of air (°C) out	Airflow (ft/min)	SO_2 conc. in (ppm)	SO_2 conc. out (ppm)	SO_2 removal %
5	22	15	500	2863	1536	46.3
5	22	15	500	3112	1896	39.1
5	22	14	500	3620	1928	46.7
5	22	14	500	2950	1438	51.2
5	22	14	500	3200	1420	55.6

*Samples taken at five minute intervals (total time running: 50 min.)

Average removal: 47.8 %.

Foaming conditions: light foaming.

Liquid to gas ratio (L/G): 0.012.

Table 52

Venturi Scrubber Test

Surfactant: Abex JKB.

Gas: Sulfur Dioxide.

Surfactant conc.: 0.02 %

Air flow: 81.0 cfm.

Liquid flow: 8.45 gpm.

SO_2 injected: 600 ppm.

Lab. Temperature: 20 °C.

Scrubbing Liquor Temp.: 10 °C.

Volume of Surfactant: 64 ml.

Volume of Solution: 82.25 gal.

Sampling Time* (min)	Temp. of air (°C) in	Temp. of air (°C) out	Airflow (ft/min)	SO_2 conc. in (ppm)	SO_2 conc. out (ppm)	SO_2 removal %
5	22	16	900	174	96	44.8
5	22	15	900	239	149	37.6
5	22	14	900	598	358	40.1
5	22	14	900	598	336	43.8
5	22	14	900	647	384	40.6

*Samples taken at five minute intervals (total time running: 50 min.)

Average removal: 45.6%.

Foaming conditions: light foaming.

Liquid to gas ratio (L/G): 0.014.

Table 53

Venturi Scrubber Test

Surfactant: Abex JKB.

Gas: Sulfur Dioxide.

Surfactant conc.: 0.03 %

Air flow: 45.0 cfm.

Liquid flow: 4.4 gpm.

SO_2 injected: 850 ppm.

Lab. Temperature: 21 °C.

Scrubbing Liquor Temp.: 13 °C.

Volume of Surfactant: 96 ml.

Volume of Solution: 82.25 gal.

Sampling Time* (min)	Temp. of air (°C) in	Temp. of air (°C) out	Airflow (ft/min)	SO_2 conc. in (ppm)	SO_2 conc. out (ppm)	SO_2 removal %
5	22	16	500	950	249	73.8
5	22	16	500	1020	285	72.1
5	22	16	500	1100	324	70.5
5	22	16	500	900	289	67.9
5	22	16	500	1200	321	73.2

*Samples taken at five minute intervals (total time running: 50 min.)

Average removal: 71.5%.

Foaming conditions: light foaming.

Liquid to gas ratio (L/G): 0.013.

Table 54

Venturi Scrubber Test

Surfactant: Abex JKB.

Gas: Sulfur Dioxide.

Surfactant conc.: 0.03%

Air flow: 81.0 cfm.

Liquid flow: 8.4 gpm.

SO_2 injected: 600 ppm.

Lab. Temperature: 21 °C.

Scrubbing Liquor Temp.: 13 °C.

Volume of Surfactant: 96 ml.

Volume of Solution: 82.25 gal.

Sampling Time* (min)	Temp. of air (°C) in	Temp. of air (°C) out	Airflow (ft/min)	SO_2 conc. in (ppm)	SO_2 conc. out (ppm)	SO_2 removal %
5	22	16	900	209	48	77.0
5	22	16	900	281	62	77.9
5	22	16	900	299	72	75.9
5	22	15	900	299	105	64.9
5	22	15	900	349	134	61.6

*Samples taken at five minute intervals (total time running: 50 min.)

Average removal: 71.5 %.

Foaming conditions: heavy foaming.

Liquid to gas ratio (L/G): 0.014.

Table 55

Venturi Scrubber Test

Surfactant: Abex JKB.

Gas: Sulfur Dioxide.

Surfactant conc.: 0.04 %

Air flow: 45.0 cfm.

Liquid flow: 5.2 gpm.

SO_2 injected: 1600 ppm.

Lab. Temperature: 22 °C.

Scrubbing Liquor Temp.: 12 °C.

Volume of Surfactant: 128 ml.

Volume of Solution: 82.25 gal.

Sampling Time* (min)	Temp. of air (°C) in	Temp. of air (°C) out	Airflow (ft/min)	SO_2 conc. in (ppm)	SO_2 conc. out (ppm)	SO_2 removal %
5	22	15	500	1550	388	74.9
5	22	15	450	1400	294	79.0
5	22	15	550	1600	400	75.0
5	22	15	500	1650	363	78.0
5	22	15	500	1600	368	77.0

*Samples taken at five minute intervals (total time running: 50 min.)

Average removal: 76.8 %.

Foaming conditions: light foaming.

Liquid to gas ratio (L/G): 0.015.

Table 56

Venturi Scrubber Test

Surfactant: Abex JKB.

Gas: Sulfur Dioxide.

Surfactant conc.: 0.04 %

Air flow: 81.0 cfm.

Liquid flow: 8.35 gpm.

SO_2 injected: 1500 ppm.

Lab. Temperature: 22 °C.

Scrubbing Liquor Temp.: 14 °C.

Volume of Surfactant: 128 ml.

Volume of Solution: 82.25 gal.

Sampling Time* (min)	Temp. of air (°C) in	Temp. of air (°C) out	Airflow (ft/min)	SO_2 conc. in (ppm)	SO_2 conc. out (ppm)	SO_2 removal %
5	21	15	900	1400	630	55.0
5	21	15	900	1450	625	56.9
5	21	15	900	1500	678	54.8
5	21	15	900	1350	595	55.9
5	21	15	900	1600	800	50.0

*Samples taken at five minute intervals (total time running: 50 min.)

Average removal: 54.5 %.

Foaming conditions: heavy foaming.

Liquid to gas ratio (L/G): 0.014.

Table 57

Venturi Scrubber Test

Surfactant: Abex JKB.

Gas: Sulfur Dioxide.

Surfactant conc.: 0.05%

Air flow: 45.0 cfm.

Liquid flow: 4.37 gpm.

SO_2 injected: 800 ppm.

Lab. Temperature: 21 °C.

Scrubbing Liquor Temp.: 13 °C.

Volume of Surfactant: 160 ml.

Volume of Solution: 82.25 gal.

Sampling Time* (min)	Temp. of air (°C) in	Temp. of air (°C) out	Airflow (ft/min)	SO_2 conc. in (ppm)	SO_2 conc. out (ppm)	SO_2 removal %
5	22	18	500	349	79	77.4
5	22	17	500	436	48	89.0
5	22	16	500	647	120	81.4
5	22	16	500	598	192	67.9
5	22	16	500	747	144	80.7

*Samples taken at five minute intervals (total time running: 50 min.)

Average removal: 79.3 %.

Foaming conditions: light foaming.

Liquid to gas ratio (L/G): 0.013.

Table 58

Venturi Scrubber Test

Surfactant: Abex JKB.

Gas: Sulfur Dioxide.

Surfactant conc.: 0.05%

Air flow: 78.3 cfm.

Liquid flow: 8.2 gpm.

SO_2 injected: 1900 ppm.

Lab. Temperature: 20 °C.

Scrubbing Liquor Temp.: 10 °C.

Volume of Surfactant: 160 ml.

Volume of Solution: 82.25 gal.

Sampling Time* (min)	Temp. of air (°C) in	Temp. of air (°C) out	Airflow (ft/min)	SO_2 conc. in (ppm)	SO_2 conc. out (ppm)	SO_2 removal %
5	22	14	900	2303	1680	27.0
5	22	14	900	2689	1520	43.5
5	22	13	900	2150	1392	35.2
5	22	13	850	2320	1562	32.7
5	22	13	850	1985	1230	38.0

*Samples taken at five minute intervals (total time running: 50 min.)

Average removal: 35.3%.

Foaming conditions: heavy foaming.

Liquid to gas ratio (L/G): 0.014.

Table 59

Venturi Scrubber Test

Surfactant: Abex JKB.
Gas: Sulfur Dioxide.

Surfactant conc.: 0.06 %
Air flow: 45.0 cfm.
Liquid flow: 4.2 gpm.
SO_2 injected: 1600 ppm.

Lab. Temperature: 21 °C.
Scrubbing Liquor Temp.: 13 °C.
Volume of Surfactant: 192 ml.
Volume of Solution: 82.25 gal.

Sampling Time* (min)	Temp. of air (°C) in	Temp. of air (°C) out	Airflow (ft/min)	SO_2 conc. in (ppm)	SO_2 conc. out (ppm)	SO_2 removal %
5	22	14	500	1650	818	60.4
5	22	14	500	1520	632	58.4
5	22	14	500	1780	752	67.7
5	22	14	500	1800	681	62.2
5	22	14	500	1520	722	52.5

*Samples taken at five minute intervals (total time running: 50 min.)

Average removal: 60.2 %.

Foaming conditions: heavy foaming.

Liquid to gas ratio (L/G): 0.012.

Table 60

Venturi Scrubber Test

Surfactant: Abex JKB.

Gas: Sulfur Dioxide.

Surfactant conc.: 0.06 %

Air flow: 74.7 cfm.

Liquid flow: 8.2 gpm.

SO_2 injected: 1500 ppm.

Lab. Temperature: 21 °C.

Scrubbing Liquor Temp.: 13 °C.

Volume of Surfactant: 192 ml.

Volume of Solution: 82.25 gal.

Sampling Time* (min)	Temp. of air (°C) in	Temp. of air (°C) out	Airflow (ft/min)	SO_2 conc. in (ppm)	SO_2 conc. out (ppm)	SO_2 removal %
5	22	14	900	1720	623	63.8
5	22	14	900	1525	528	65.4
5	22	14	850	1480	623	57.9
5	22	14	800	1650	745	54.8
5	22	13	700	1800	818	54.5

*Samples taken at five minute intervals (total time running: 50 min.)

Average removal: 59.3%.

Foaming conditions: heavy foaming.

Liquid to gas ratio (L/G): 0.015.

Table 61

Venturi Scrubber Test

Surfactant: Abex JKB. Gas: Sulfur Dioxide.

Surfactant conc.: 0.07 %

Air flow: 45.0 cfm.

Liquid flow: 4.3 gpm.

SO_2 injected: 3500 ppm.

Lab. Temperature: 21 °C.

Scrubbing Liquor Temp.: 13 °C.

Volume of Surfactant: 224 ml.

Volume of Solution: 82.25 gal.

Sampling Time* (min)	Temp. of air (°C) in	Temp. of air (°C) out	Airflow (ft/min)	SO_2 conc. in (ppm)	SO_2 conc. out (ppm)	SO_2 removal %
5	22	14	500	3984	2400	39.7
5	22	14	500	3984	2328	41.6
5	22	14	500	3486	2256	35.3
5	22	14	500	3520	2320	34.1
5	22	14	500	3720	2560	31.2

*Samples taken at five minute intervals (total time running: 50 min.)

Average removal: 36.4 %.

Foaming conditions: light foaming.

Liquid to gas ratio (L/G): 0.013.

Table 62

Venturi Scrubber Test

Surfactant: Abex JKB.

Gas: Sulfur Dioxide.

Surfactant conc.: 0.07 %

Air flow: 65.7 cfm.

Liquid flow: 8.25 gpm.

SO_2 injected: 2400 ppm.

Lab. Temperature: 21 °C.

Scrubbing Liquor Temp.: 13 °C.

Volume of Surfactant: 224 ml.

Volume of Solution: 82.25 gal.

Sampling Time* (min)	Temp. of air (°C) in	Temp. of air (°C) out	Airflow (ft/min)	SO_2 conc. in (ppm)	SO_2 conc. out (ppm)	SO_2 removal %
5	22	14	950	1295	576	55.5
5	22	14	850	1992	816	59.0
5	22	14	700	2091	816	61.0
5	22	14	600	3112	864	72.2
5	22	14	550	2988	912	69.5

*Samples taken at five minute intervals (total time running: 50 min.)

Average removal: 63.4 %.

Foaming conditions: heavy foaming.

Liquid to gas ratio (L/G): 0.017.

Figure (13)

Removal Efficiency (%) versus Time

Surfactant: Cenetol HS

Air Flow Rate: 45.0 cfm.

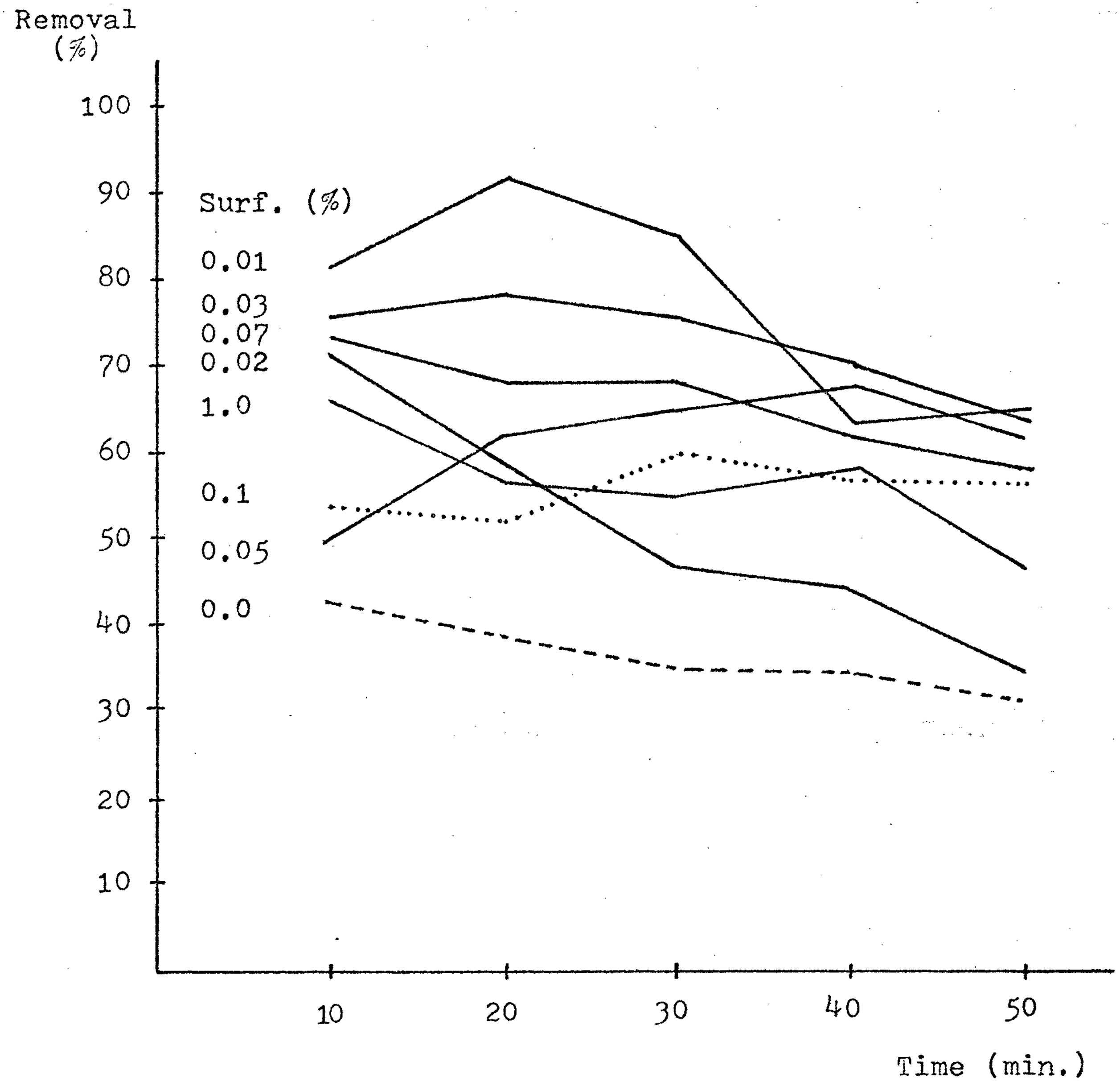


Figure (14)

Removal Efficiency (%) versus Time

Surfactant: Cenetol HS

Air Flow Rate: 81.0 cfm.

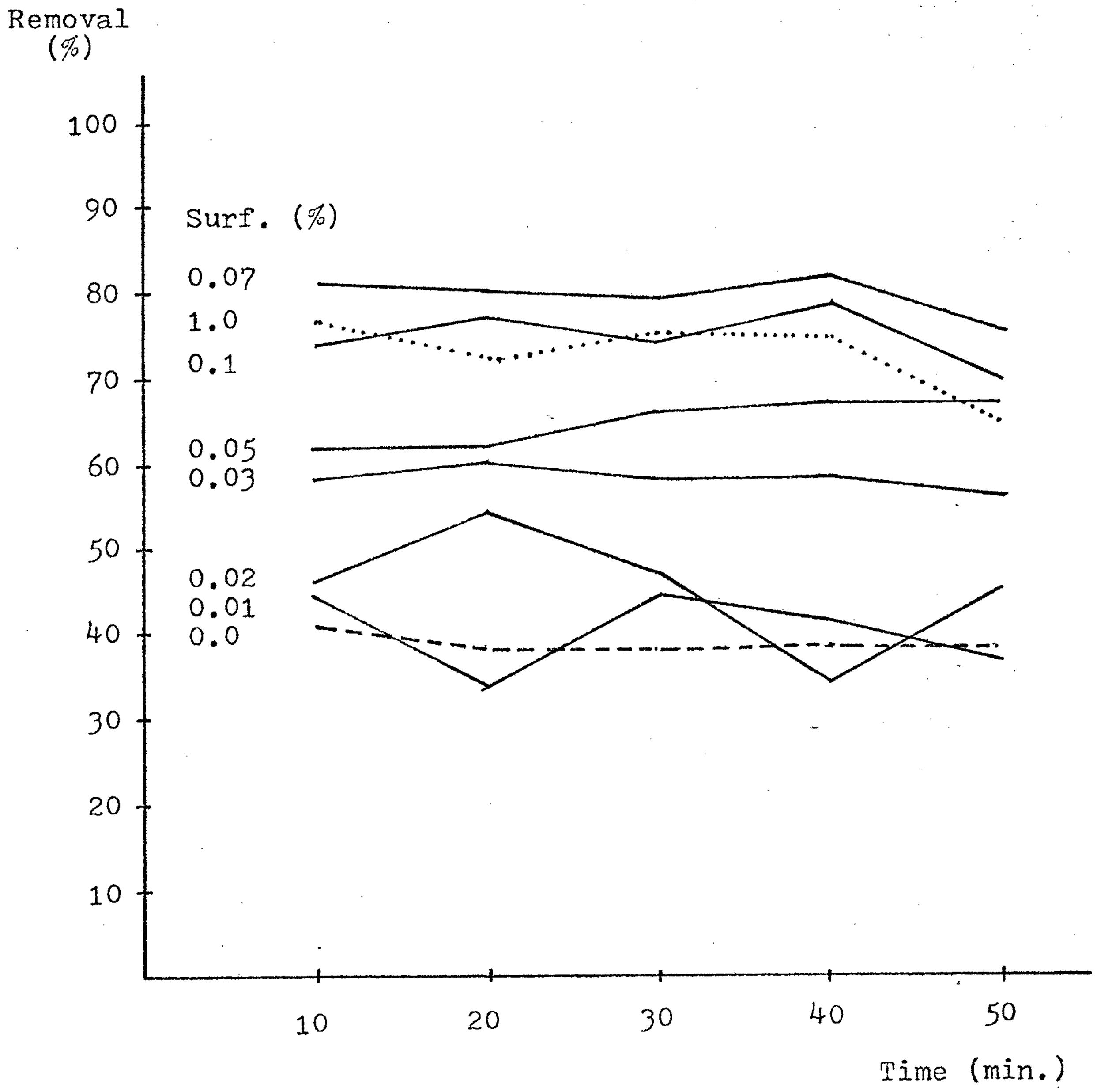


Table (63)

Venturi Scrubber Test

Surfactant: Cenetol HS.

Gas: Sulfur Dioxide.

Surfactant conc.:0.01 %

Air flow: 46.8 cfm.

Liquid flow: 5.7 gpm.

SO_2 injected: 1200 ppm.

Lab. Temperature: 21 °C.

Scrubbing Liquor Temp.: 16 °C.

Volume of Surfactant: 32 ml.

Volume of Solution: 82.25 gal.

Sampling Time* (min)	Temp. of air (°C) in	Temp. of air (°C) out	Airflow (ft/min)	SO_2 conc. in (ppm)	SO_2 conc. out (ppm)	SO_2 removal %
5	22	15	500	548	106	80,6
5	22	15	500	958	90	90.6
5	22	14	500	958	153	84.0
5	22	14	550	1295	480	62.9
5	22	14	550	1419	504	64.5

*Samples taken at five minute intervals (total time running: 50 min.)

Average removal: 76.5 %.

Foaming conditions: no foaming.

Liquid to gas ratio (L/G): 0.016.

Table 64

Venturi Scrubber Test

Surfactant: Cenetol HS.

Gas: Sulfur Dioxide.

Surfactant conc.: 0.01 %

Air flow: 81.9 cfm.

Liquid flow: 6.7 gpm.

SO_2 injected: 1500 ppm.

Lab. Temperature: 21 °C.

Scrubbing Liquor Temp.: 16 °C.

Volume of Surfactant: 32 ml.

Volume of Solution: 82.25 gal.

Sampling Time* (min)	Temp. of air (°C) in	Temp. of air (°C) out	Airflow (ft/min)	SO_2 conc. in (ppm)	SO_2 conc. out (ppm)	SO_2 removal %
5	22	16	900	1295	720	44.4
5	22	16	900	1295	864	33.3
5	22	15	900	1892	1056	44.2
5	22	15	900	2116	1248	41.0
5	22	15	950	2116	1343	36.5

*Samples taken at five minute intervals (total time running: 50 min.)

Average removal: 39.9 %.

Foaming conditions: no foaming.

Liquid to gas ratio (L/G): 0.011.

Table 65

Venturi Scrubber Test

Surfactant: Cenetol HS.

Gas: Sulfur Dioxide.

Surfactant conc.: 0.02 %

Air flow: 45.0 cfm.

Liquid flow: 5.2 gpm.

SO_2 injected: 950 ppm.

Lab. Temperature: 21 °C.

Scrubbing Liquor Temp.: 13 °C.

Volume of Surfactant: 64 ml.

Volume of Solution: 82.25 gal.

Sampling Time* (min)	Temp. of air (°C) in	Temp. of air (°C) out	Airflow (ft/min)	SO_2 conc. in (ppm)	SO_2 conc. out (ppm)	SO_2 removal %
5	22	16	500	660	192	70.9
5	22	16	500	946	384	59.4
5	22	16	500	946	504	46.7
5	22	16	500	1070	600	43.9
5	22	16	500	946	624	34.0

*Samples taken at five minute intervals (total time running: 50 min.)

Average removal: 50.9 %.

Foaming conditions: no foaming.

Liquid to gas ratio (L/G): 0.015.

Table 66

Venturi Scrubber Test

Surfactant: Cenetol HS.　　Gas: Sulfur Dioxide.

Surfactant conc.: 0.02%

Air flow: 84.6 cfm.

Liquid flow: 8.45 gpm.

SO_2 injected: 1000 ppm.

Lab. Temperature: 21 °C.

Scrubbing Liquor Temp.: 13 °C.

Volume of Surfactant: 64 ml.

Volume of Solution: 82.25 gal.

Sampling Time* (min)	Temp. of air (°C) in	Temp. of air (°C) out	Airflow (ft/min)	SO_2 conc. in (ppm)	SO_2 conc. out (ppm)	SO_2 removal %
5	22	16	900	946	504	46.7
5	22	15	950	1070	504	52.9
5	22	15	950	1120	600	46.4
5	22	15	950	946	624	34.0
5	22	15	950	1120	624	44.3

*Samples taken at five minute intervals (total time running: 50 min.)

Average removal: 44.9 %.

Foaming conditions: no foaming.

Liquid to gas ratio (L/G): 0.013.

Table 67

Venturi Scrubber Test

Surfactant: Cenetol HS.

Gas: Sulfur Dioxide.

Surfactant conc.: 0.03 %

Air flow: 45.0 cfm.

Liquid flow: 5.3 gpm.

SO_2 injected: 1750 ppm.

Lab. Temperature: 22 °C.

Scrubbing Liquor Temp.: 13 °C.

Volume of Surfactant: 96 ml.

Volume of Solution: 82.25 gal.

Sampling Time* (min)	Temp. of air (°C) in	Temp. of air (°C) out	Airflow (ft/min)	SO_2 conc. in (ppm)	SO_2 conc. out (ppm)	SO_2 removal %
5	22	15	500	1800	446	75.2
5	22	15	500	1750	394	77.5
5	22	15	500	1700	425	75.0
5	22	15	500	1700	510	70.0
5	22	15	500	1750	478	72.7

*Samples taken at five minute intervals (total time running: 50 min.)

Average removal: 74.1 %.

Foaming conditions: no foaming.

Liquid to gas ratio (L/G): 0.017.

Table 68

Venturi Scrubber Test

Surfactant: Cenetol HS. | Gas: Sulfur Dioxide.

Surfactant conc.: 0.03 %
Air flow: 81.0 cfm.
Liquid flow: 8.4 gpm.
SO_2 injected: 1600 ppm.

Lab. Temperature: 22 °C.
Scrubbing Liquor Temp.: 13 °C.
Volume of Surfactant: 96 ml.
Volume of Solution: 82.25 gal.

Sampling Time* (min)	Temp. of air (°C) in	Temp. of air (°C) out	Airflow (ft/min)	SO_2 conc. in (ppm)	SO_2 conc. out (ppm)	SO_2 removal %
5	22	14	900	1500	636	57.6
5	22	14	900	1550	623	59.8
5	22	14	900	1600	680	57.5
5	22	14	900	1600	688	57.0
5	22	14	900	1650	738	55.3

*Samples taken at five minute intervals (total time running: 50 min.)

Average removal: 57.4 %.

Foaming conditions: no foaming.

Liquid to gas ratio (L/G): 0.014.

Table 69

Venturi Scrubber Test

Surfactant: Cenetol HS.

Gas: Sulfur Dioxide.

Surfactant conc.: 0.05 %

Air flow: 45.0 cfm.

Liquid flow: 5.7 gpm.

SO_2 injected: 1250 ppm.

Lab. Temperature: 21 °C.

Scrubbing Liquor Temp.: 13 °C.

Volume of Surfactant: 160 ml.

Volume of Solution: 82.25 gal.

Sampling Time* (min)	Temp. of air (°C) in	Temp. of air (°C) out	Airflow (ft/min)	SO_2 conc. in (ppm)	SO_2 conc. out (ppm)	SO_2 removal %
5	22	16	500	1285	650	49.1
5	22	16	500	1320	525	60.2
5	22	16	500	1425	518	63.6
5	22	15	500	1300	425	67.3
5	22	15	500	1250	485	61.2

*Samples taken at five minute intervals (total time running: 50 min.)

Average removal: 60.3 %.

Foaming conditions: no foaming.

Liquid to gas ratio (L/G): 0.017.

Table 70

Venturi Scrubber Test

Surfactant: Cenetol HS. Gas: Sulfur Dioxide.

Surfactant conc.:	0.05 %	Lab. Temperature:	21 °C.
Air flow:	81.0 cfm.	Scrubbing Liquor Temp.:	14 °C.
Liquid flow:	6.7 gpm.	Volume of Surfactant:	160 ml.
SO_2 injected:	1200 ppm.	Volume of Solution:	82.25 gal.

Sampling Time* (min)	Temp. of air (°C) in	Temp. of air (°C) out	Airflow (ft/min)	SO_2 conc. in (ppm)	SO_2 conc. out (ppm)	SO_2 removal %
5	22	15	900	985	386	60.8
5	22	15	900	910	352	61.3
5	22	15	900	1220	425	65.2
5	22	15	900	1150	389	66.2
5	22	15	900	1085	372	65.7

*Samples taken at five minute intervals (total time running: 50 min.)

Average removal: 63.8 %.

Foaming conditions: light foaming.

Liquid to gas ratio (L/G): 0.011.

Table 71

Venturi Scrubber Test

Surfactant: Cenetol HS.

Gas: Sulfur Dioxide.

Surfactant conc.: 0.07 %

Air flow: 45.0 cfm.

Liquid flow: 5.3 gpm.

SO_2 injected: 1650 ppm.

Lab. Temperature: 22 °C.

Scrubbing Liquor Temp.: 14 °C.

Volume of Surfactant: 224 ml.

Volume of Solution: 82.25 gal.

Sampling Time* (min)	Temp. of air (°C) in	Temp. of air (°C) out	Airflow (ft/min)	SO_2 conc. in (ppm)	SO_2 conc. out (ppm)	SO_2 removal %
5	22	15	500	1600	438	72.6
5	22	15	500	1550	502	67.6
5	22	15	500	1500	483	67.8
5	22	15	500	1500	573	61.8
5	22	15	500	1550	654	57.8

*Samples taken at five minute intervals (total time running: 50 min.)

Average removal: 65.5 %.

Foaming conditions: light foaming.

Liquid to gas ratio (L/G): 0.016.

Table 72

Venturi Scrubber Test

Surfactant: Cenetol HS. Gas: Sulfur Dioxide.

Surfactant conc.: 0.07 %

Air flow: 81.0 cfm.

Liquid flow: 8.3 gpm.

SO_2 injected: 1500 ppm.

Lab. Temperature: 22 °C.

Scrubbing Liquor Temp.: 14 °C.

Volume of Surfactant: 224 ml.

Volume of Solution: 82.25 gal.

Sampling Time* (min)	Temp. of air (°C) in	Temp. of air (°C) out	Airflow (ft/min)	SO_2 conc. in (ppm)	SO_2 conc. out (ppm)	SO_2 removal %
5	22	14	900	1500	285	81.0
5	22	14	900	1400	280	80.0
5	22	14	900	1450	312	78.5
5	22	14	900	1600	288	82.0
5	22	14	900	1500	375	75.0

*Samples taken at five minute intervals (total time running: 50 min.)

Average removal: 79.3 %.

Foaming conditions: light foaming.

Liquid to gas ratio (L/G): 0.014.

Table 73

Venturi Scrubber Test

Surfactant: Cenetol HS. Gas: Sulfur Dioxide.

Surfactant conc.: 0.1 %

Air flow: 45.0 cfm.

Liquid flow: 5.2 gpm.

SO_2 injected: 1200 ppm.

Lab. Temperature: 21 °C.

Scrubbing Liquor Temp.: 13 °C.

Volume of Surfactant: 320 ml.

Volume of Solution: 82.25 gal.

Sampling Time* (min)	Temp. of air (°C) in	Temp. of air (°C) out	Airflow (ft/min)	SO_2 conc. in (ppm)	SO_2 conc. out (ppm)	SO_2 removal %
5	22	15	500	1419	672	52.6
5	22	15	500	1295	624	51.8
5	22	15	500	1490	600	59.7
5	22	15	500	1120	485	56.7
5	22	15	500	1419	632	55.5

*Samples taken at five minute intervals (total time running: 50 min.)

Average removal: 48.6 %.

Foaming conditions: no foaming.

Liquid to gas ratio (L/G): 0.015.

Table 74

Venturi Scrubber Test

Surfactant: Cenetol HS.

Gas: Sulfur Dioxide.

Surfactant conc.: 0.1 %

Air flow: 81.0 cfm.

Liquid flow: 8.2 gpm.

SO_2 injected: 1900 ppm.

Lab. Temperature: 21 °C.

Scrubbing Liquor Temp.: 13 °C.

Volume of Surfactant: 320 ml.

Volume of Solution: 82.25 gal.

Sampling Time* (min)	Temp. of air (°C) in	Temp. of air (°C) out	Airflow (ft/min)	SO_2 conc. in (ppm)	SO_2 conc. out (ppm)	SO_2 removal %
5	22	16	900	1892	504	73.4
5	22	16	900	2116	480	77.3
5	22	16	900	1942	528	72.8
5	22	15	900	2266	504	77.8
5	22	15	900	1892	600	68.3

*Samples taken at five minute intervals (total time running: 50 min.)

Average removal: 73.9 %.

Foaming conditions: light foaming.

Liquid to gas ratio (L/G): 0.013.

Table 75

Venturi Scrubber Test

Surfactant: Cenetol HS.

Gas: Sulfur Dioxide.

Surfactant conc.: 1.0 %

Air flow: 45.0 cfm.

Liquid flow: 4.4 gpm.

SO_2 injected: 700 ppm.

Lab. Temperature: 21 °C.

Scrubbing Liquor Temp.: 17 °C.

Volume of Surfactant: 3100 ml.

Volume of Solution: 82.25 gal.

Sampling Time* (min)	Temp. of air (°C) in	Temp. of air (°C) out	Airflow (ft/min)	SO_2 conc. in (ppm)	SO_2 conc. out (ppm)	SO_2 removal %
5	22	17	500	548	182	66.8
5	22	17	500	448	192	57.1
5	22	17	500	480	216	55.0
5	22	17	500	448	192	57.1
5	22	17	500	460	251	45.4

*Samples taken at five minute intervals (total time running: 50 min.)

Average removal: 60.5%.

Foaming conditions: light foaming.

Liquid to gas ratio (L/G): 0.013.

Table 76

Venturi Scrubber Test

Surfactant: Cenetol HS.

Gas: Sulfur Dioxide.

Surfactant conc.: 1.0 %

Air flow: 81.0 cfm.

Liquid flow: 6.6 gpm.

SO_2 injected: 1100 ppm.

Lab. Temperature: 21 °C.

Scrubbing Liquor Temp.: 17 °C.

Volume of Surfactant: 3100 ml.

Volume of Solution: 82.25 gal.

Sampling Time* (min)	Temp. of air (°C) in	Temp. of air (°C) out	Airflow (ft/min)	SO_2 conc. in (ppm)	SO_2 conc. out (ppm)	SO_2 removal %
5	22	16	900	946	221	76.6
5	22	16	900	772	216	72.0
5	22	16	900	875	223	74.5
5	22	16	900	1120	295	73.7
5	22	16	900	1070	384	64.1

*Samples taken at five minute intervals (total time running: 50 min.)

Average removal: 72.2 %.

Foaming conditions: very heavy foaming.

Liquid to gas ratio (L/G): 0.012.

Figure(15)

Removal Efficiency (%) versus Time

Surfactant: Armohib 31

Air Flow Rate: 45.0 cfm.

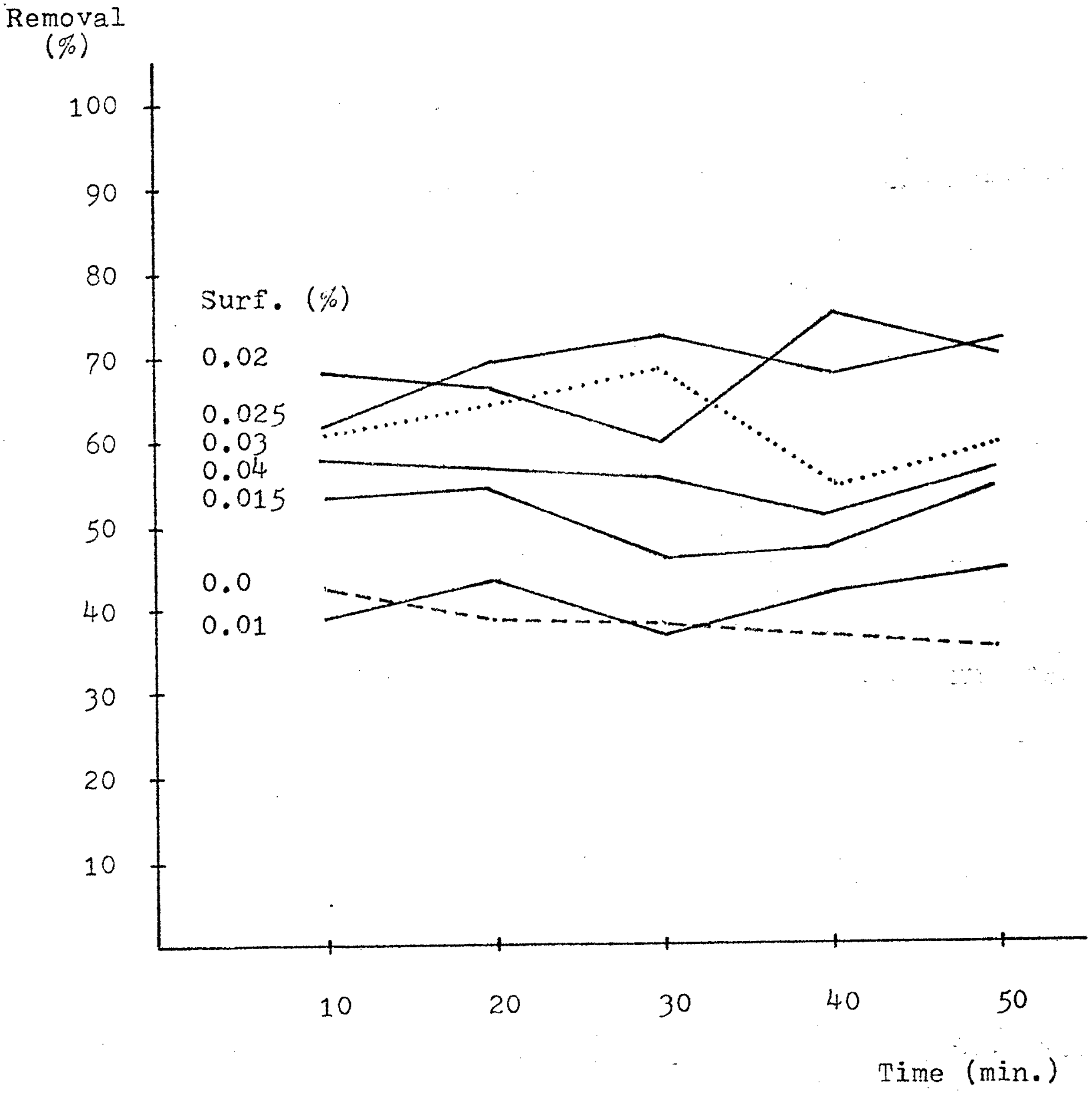


Figure (16)

Removal Efficiency (%) versus Time

Surfactant: Armohib 31

Air Flow Rate: 81.0 cfm.

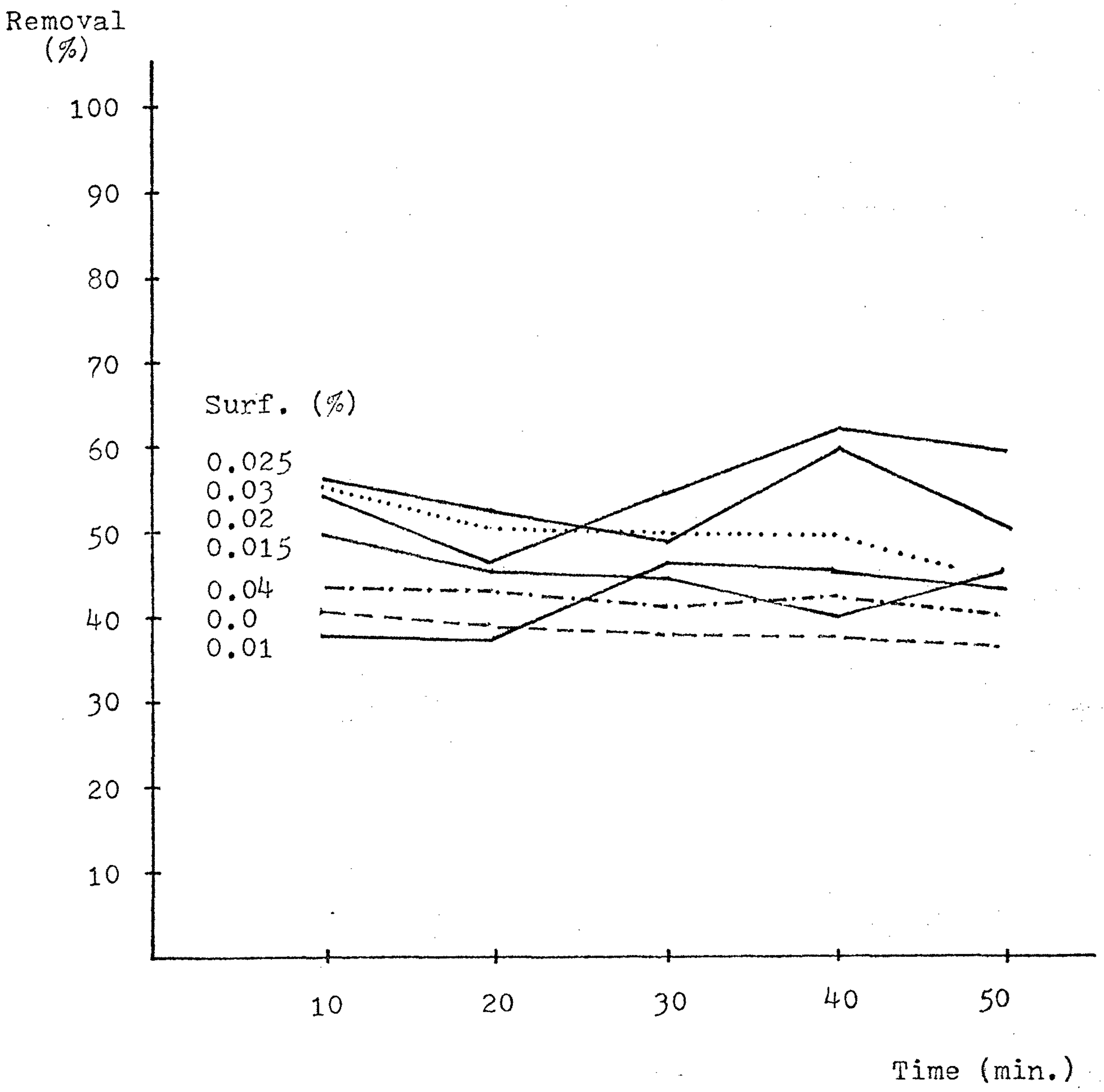


Table 77

Venturi Scrubber Test

Surfactant: Armohib 31. Gas: Sulfur Dioxide.

Surfactant conc.:	0.01 %	Lab. Temperature:	21 °C.
Air flow:	45.0 cfm.	Scrubbing Liquor Temp.:	13 °C.
Liquid flow:	5.9 gpm.	Volume of Surfactant:	32 ml.
SO_2 injected:	900 ppm.	Volume of Solution:	82.25 gal.

Sampling Time* (min)	Temp. of air (°C) in	Temp. of air (°C) out	Airflow (ft/min)	SO_2 conc. in (ppm)	SO_2 conc. out (ppm)	SO_2 removal %
5	22	14	500	946	576	39.1
5	22	14	500	1095	624	43.0
5	22	14	500	1145	720	37.1
5	22	14	500	1444	852	41.0
5	22	14	500	1258	720	42.8

*Samples taken at five minute intervals (total time running: 50 min.)

Average removal: 43.1 %.

Foaming conditions: light foaming.

Liquid to gas ratio (L/G): 0.017.

Table 78

Venturi Scrubber Test

Surfactant: Armohib 31. Gas: Sulfur Dioxide.

Surfactant conc.: 0.01 % Lab. Temperature: 21 °C.

Air flow: 79.2 cfm. Scrubbing Liquor Temp.: 13 °C.

Liquid flow: 8.7 gpm. Volume of Surfactant: 32 ml.

SO_2 injected: 1000 ppm. Volume of Solution: 82.25 gal.

Sampling Time* (min)	Temp. of air (°C) in	Temp. of air (°C) out	Airflow (ft/min)	SO_2 conc. in (ppm)	SO_2 conc. out (ppm)	SO_2 removal %
5	22	14	850	980	612	37.5
5	22	14	900	1150	724	37.0
5	22	14	900	1200	658	45.2
5	22	14	850	985	548	44.4
5	22	14	900	850	489	42.5

*Samples taken at five minute intervals (total time running: 50 min.)

Average removal: 41.3 %.

Foaming conditions: heavy foaming.

Liquid to gas ratio (L/G): 0.015.

Table 79

Venturi Scrubber Test

Surfactant: Armohib 31	Gas: Sulfur Dioxide.
Surfactant conc.: 0.02%	Lab. Temperature: 21 °C.
Air flow: 43.2 cfm.	Scrubbing Liquor Temp.: 13 °C.
Liquid flow: 5.4 gpm.	Volume of Surfactant: 64 ml.
SO_2 injected: 1500 ppm.	Volume of Solution: 82.25 gal.

Sampling Time* (min)	Temp. of air (°C) in	Temp. of air (°C) out	Airflow (ft/min)	SO_2 conc. in (ppm)	SO_2 conc. out (ppm)	SO_2 removal %
5	22	14	500	886	285	67.8
5	22	14	450	1320	460	65.1
5	22	14	450	1892	768	59.4
5	22	14	500	1789	463	74.1
5	22	14	500	1892	576	69.5

*Samples taken at five minute intervals (total time running: 50 min.)

Average removal: 70.9 %.

Foaming conditions: light foaming.

Liquid to gas ratio (L/G): 0.017.

Table 80

Venturi Scrubber Test

Surfactant: Armohib 31.	Gas: Sulfur Dioxide.
Surfactant conc.: 0.02 %	Lab. Temperature: 21°C.
Air flow: 77.4 cfm.	Scrubbing Liquor Temp.: 13°C.
Liquid flow: 8.6 gpm.	Volume of Surfactant: 64 ml.
SO_2 injected: 2600 ppm.	Volume of Solution: 82.25 gal.

Sampling Time* (min)	Temp. of air (°C) in	Temp. of air (°C) out	Airflow (ft/min)	SO_2 conc. in (ppm)	SO_2 conc. out (ppm)	SO_2 removal %
5	22	14	1000	1843	840	54.4
5	22	14	950	2116	1152	45.5
5	22	14	850	2758	1248	54.7
5	22	14	800	3112	1198	61.5
5	22	14	700	3287	1368	58.4

*Samples taken at five minute intervals (total time running: 50 min.)

Average removal: 54.6 %.

Foaming conditions: heavy foaming.

Liquid to gas ratio (L/G): 0.015.

Table 81

Venturi Scrubber Test

Surfactant: Armohib 31. Gas: Sulfur Dioxide.

Surfactant conc.: 0.015%
Air flow: 45.0 cfm.
Liquid flow: 5.9 gpm.
SO_2 injected: 1500 ppm.

Lab. Temperature: 21 °C.
Scrubbing Liquor Temp.: 14 °C.
Volume of Surfactant: 48 ml.
Volume of Solution: 82.25 gal.

Sampling Time* (min)	Temp. of air (°C) in	Temp. of air (°C) out	Airflow (ft/min)	SO_2 conc. in (ppm)	SO_2 conc. out (ppm)	SO_2 removal %
5	22	16	500	1120	528	52.8
5	22	16	500	1394	648	53.5
5	22	15	500	1581	864	45.3
5	22	15	500	1992	1080	45.8
5	22	15	500	1842	858	53.4

*Samples taken at five minute intervals (total time running: 50 min.)

Average removal: 45.9 %.

Foaming conditions: light foaming.

Liquid to gas ratio (L/G): 0.017.

Table 82

Venturi Scrubber Test

Surfactant: Armohib 31. Gas: Sulfur Dioxide.

Surfactant conc.: 0.015%

Air flow: 78.3 cfm.

Liquid flow: 8.2 gpm.

SO_2 injected: 1400 ppm.

Lab. Temperature: 21 °C.

Scrubbing Liquor Temp.: 14 °C.

Volume of Surfactant: 48 ml.

Volume of Solution: 82.25 gal.

Sampling Time* (min)	Temp. of air (°C) in	Temp. of air (°C) out	Airflow (ft/min)	SO_2 conc. in (ppm)	SO_2 conc. out (ppm)	SO_2 removal %
5	22	15	900	1320	670	49.2
5	22	15	900	1285	694	45.9
5	22	15	850	1420	788	44.5
5	22	15	850	1382	834	39.6
5	22	15	850	1225	691	43.6

*Samples taken at five minute intervals (total time running: 50 min.)

Average removal: 44.6%.

Foaming conditions: heavy foaming.

Liquid to gas ratio (L/G): 0.014.

Table 83

Venturi Scrubber Test

Surfactant: Armohib 31.

Gas: Sulfur Dioxide.

Surfactant conc.:0.025%

Air flow: 45.9 cfm.

Liquid flow: 5.8 gpm.

SO_2 injected: 1200 ppm.

Lab. Temperature: 21 °C.

Scrubbing Liquor Temp.: 14 °C.

Volume of Surfactant: 80 ml.

Volume of Solution: 82.25 gal.

Sampling Time* (min)	Temp. of air (°C) in	Temp. of air (°C) out	Airflow (ft/min)	SO_2 conc. in (ppm)	SO_2 conc. out (ppm)	SO_2 removal %
5	22	15	500	1580	625	60.4
5	22	15	500	1385	445	67.9
5	22	15	550	1420	415	70.8
5	22	15	500	1300	428	67.1
5	22	15	500	1250	368	70.6

*Samples taken at five minute intervals (total time running: 50 min.)

Average removal: 67.4 %.

Foaming conditions: heavy foaming.

Liquid to gas ratio (L/G): 0.017.

Table 84

Venturi Scrubber Test

Surfactant: Armohib 31.

Gas: Sulfur Dioxide.

Surfactant conc.: 0.025%

Air flow: 77.4 cfm.

Liquid flow: 8.3 gpm.

SO_2 injected: 1500 ppm.

Lab. Temperature: 21 °C.

Scrubbing Liquor Temp.: 14 °C.

Volume of Surfactant: 80 ml.

Volume of Solution: 82.25 gal.

Sampling Time* (min)	Temp. of air (°C) in	Temp. of air (°C) out	Airflow (ft/min)	SO_2 conc. in (ppm)	SO_2 conc. out (ppm)	SO_2 removal %
5	22	15	900	1625	725	55.4
5	22	15	900	1580	758	52.0
5	22	15	900	1320	692	47.6
5	22	15	800	1680	690	58.9
5	22	14	800	1200	632	47.3

*Samples taken at five minute intervals (total time running: 50 min.)

Average removal: 52.4 %.

Foaming conditions: heavy foaming.

Liquid to gas ratio (L/G): 0.014.

Table 85

Venturi Scrubber Test

Surfactant: Armohib 31.
Gas: Sulfur Dioxide.

Surfactant conc.: 0.03%
Air flow: 45.0 cfm.
Liquid flow: 5.7 gpm.
SO_2 injected: 1600 ppm.

Lab. Temperature: 21 °C.
Scrubbing Liquor Temp.: 14 °C.
Volume of Surfactant: 96 ml.
Volume of Solution: 82.25 gal.

Sampling Time* (min)	Temp. of air (°C) in	Temp. of air (°C) out	Airflow (ft/min)	SO_2 conc. in (ppm)	SO_2 conc. out (ppm)	SO_2 removal %
5	22	14	500	1850	725	60,8
5	22	14	500	1720	632	63.2
5	22	14	500	1630	526	67.7
5	22	14	500	1800	816	54.7
5	22	14	500	1500	623	58.5

*Samples taken at five minute intervals (total time running: 50 min.)

Average removal: 60.9 %.

Foaming conditions: very heavy foaming.

Liquid to gas ratio (L/G): 0.017.

Table 86

Venturi Scrubber Test

Surfactant: Armohib 31.

Gas: Sulfur Dioxide.

Surfactant conc.: 0.03 %

Air flow: 67.5 cfm.

Liquid flow: 7.9 gpm.

SO_2 injected: 1650 ppm.

Lab. Temperature: 21 °C.

Scrubbing Liquor Temp.: 14 °C.

Volume of Surfactant: 96 ml.

Volume of Solution: 82.25 gal.

Sampling Time* (min)	Temp. of air (°C) in	Temp. of air (°C) out	Airflow (ft/min)	SO_2 conc. in (ppm)	SO_2 conc. out (ppm)	SO_2 removal %
5	22	14	900	1920	853	55.6
5	22	14	850	1870	925	50.5
5	22	14	700	1563	785	49.8
5	22	14	650	1825	918	49.7
5	22	14	650	1400	786	43.8

*Samples taken at five minute intervals (total time running: 50 min.)

Average removal: 49.9 %.

Foaming conditions: very heavy foaming.

Liquid to gas ratio (L/G): 0.016.

Table 87

Venturi Scrubber Test

Surfactant: Armohib 31. Gas: Sulfur Dioxide.

Surfactant conc.: 0.04% Lab. Temperature: 21 °C.

Air flow: 45.0 cfm. Scrubbing Liquor Temp.: 14 °C.

Liquid flow: 5.2 gpm. Volume of Surfactant: 128 ml.

SO_2 injected: 1450 ppm. Volume of Solution: 82.25 gal.

Sampling Time* (min)	Temp. of air (°C) in	Temp. of air (°C) out	Airflow (ft/min)	SO_2 conc. in (ppm)	SO_2 conc. out (ppm)	SO_2 removal %
5	22	16	500	1500	638	57.5
5	22	16	500	1450	626	56.8
5	22	16	500	1500	672	55.2
5	22	16	500	1350	665	50.7
5	22	16	500	1400	613	56.2

*Samples taken at five minute intervals (total time running: 50 min.)

Average removal: 55.3 %.

Foaming conditions: very heavy foaming.

Liquid to gas ratio (L/G): 0.015.

Table 88

Venturi Scrubber Test

Surfactant: Armohib 31.　　Gas: Sulfur Dioxide.

Surfactant conc.: 0.04 %　　Lab. Temperature: 21 °C.

Air flow: 81.0 cfm.　　Scrubbing Liquor Temp.: 14 °C.

Liquid flow: 8.4 gpm.　　Volume of Surfactant: 128 ml.

SO_2 injected: 1500 ppm.　　Volume of Solution: 82.25 gal.

Sampling Time* (min)	Temp. of air (°C) in	Temp. of air (°C) out	Airflow (ft/min)	SO_2 conc. in (ppm)	SO_2 conc. out (ppm)	SO_2 removal %
5	22	15	900	1450	827	42.9
5	22	15	900	1500	861	42.6
5	22	15	900	1400	830	40.7
5	22	14	900	1550	897	42.1
5	22	14	900	1500	863	42.5

*Samples taken at five minute intervals (total time running: 50 min.)

Average removal: 42.2 %.

Foaming conditions: very heavy foaming.

Liquid to gas ratio (L/G): 0.014.

CONCLUSIONS AND RECOMMENDATIONS

Several attempts have been made in the past few years to improve the solubility of organic vapors by scrubbing techniques with surfactant solutions. Following the same technique, the author performed experiments on six surfactants to enhance sulfur dioxide scrubbing with the ejector venturi scrubber. Results were found to be very promising, however, some further research has to be done.

Relatively high concentrations of sulfur dioxide were tested, ranging from about 400 to 4000 ppm. These concentrations are very common in several industrial processes. All the experiments were carried out at room temperature (21 ± 2).

Foaming conditions were the limiting factor at both air flow tested, 45.0 and 81,0 cfm. As a consequence, steady state conditions were impossible to obtain during the scrubbing process. Besides, some variations in the air flow rate, the liquid flow rate, the liquid to gas ratio, and the concentration of the scrubbing solution made difficult the isolation of the variables affecting the sulfur dioxide scrubbing process.

Arsil 303-E was the surfactant which exhibited the best results. The highest removal efficiency, greater than 90 % was obtained at 0.01 % surfactant concentration, the lowest in the tested range, at 45.0 cfm. Satisfactory removals were also obtained at 81.0 cfm air flow when concentrations lower than 0.04 % were tested.

Cenetol HS gave satisfactory results at 45.0 cfm air flow, but foaming problems appeared when air flow was increased to 81.0 cfm. These problems were easily solved by foam destruction.

With Emulsynt 2400 foaming conditions developed, but operating conditions were stable. Although heavy foaming occurred, the foams were easily destroyed and returned back to the solution. Therefore, this product is recommended in the surfactant enhanced scrubbing of sulfur dioxide.

Although Abex JKB and Armohib 31 gave relatively high removal efficiencies, these products are not recommended because the foams made both the operation and the maintenance of the system very difficult.

Results with Mafo 13 were not very satisfactory and heavy foaming made the scrubbing process very difficult.

It is recommended that experiments be carried out to study the effects of longer residence times inside the pilot scrubber. It is also recommended that other kinds of surfactants, different from the ones tested, be examined.

FOOTNOTES

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