Absorption of H_2S in NaOCl Caustic Aqueous Solution

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Pilot plant experimental data were collected to study the feasibility of H_2S removal from air streams utilizing aqueous solutions. Solutions of NaOCl/NaOH were tested in a packed bed scrubber and found to be effective. An efficiency of 99.2% H_2S removal was achieved at a gas flow rate of 790 lb/ft^2-hr and liquid-gas ratio of 5.06. Sodium hydroxide was found to be the active ingredient in the absorption process. A minimum alkalinity of pH 11 in the scrubbing solution was required for the H_2S to be efficiently absorbed in the packed bed scrubber. For gas flow rates up to 2,100 lb/ft^2 hr, the height of a transfer unit (HTU) varied from 1.8 ft to 2 ft with different proportions of NaOCl and NaOH in the solution.

INTRODUCTION

Hydrogen sulfide (H_2S) is produced in nature by anaerobic decomposition of sulfur-containing organic and inorganic matter. In recent years, industrial activities have contributed substantially to H_2S emissions through hydrogenation and hydrodesulfurization processes, and through anaerobic, thermal treatment processes, such as in coke ovens. No matter how it is produced, H_2S poses a serious health risk, not to mention an obnoxious odor. The human nose can detect the “rotten egg” odor of H_2S at a concentration of 0.4 parts per billion (ppb). The maximum allowable exposure for prolonged periods is 10 parts per million (ppm), the peak concentration for 10 minutes exposure is 50 ppm and exposure to concentrations greater than 300 ppm for 30 minutes is fatal [1].

The two main purposes for removing H_2S from gas streams are to purify synthetic gas and to achieve air pollutants control. For these goals, numerous methodologies have been developed, and more than half a dozen have been demonstrated commercially. Among these methods are amine absorption, alkaline salt absorption, dry oxidation, liquid phase oxidation and H_2S scavengers for gas purification and adsorption [2], and caustic absorption and chemical oxidation for end-of-pipe odor control [3].

Aqueous amine solutions have been used commercially since the 1930s to remove acid gases, such as CO_2 and H_2S, from a variety of hydrocarbon-based gas streams, including natural gas, refinery gas, coke oven gas, etc. Amine absorption units absorb the H_2S and other acid compounds into an aqueous solution, which is then heated. Heating regenerates the lean amine solution, while releasing a concentrated H_2S gas stream. Generally, amine absorption units are limited to anaerobic gas streams since oxygen will oxidize the amines [4].

In the Claus Process, widely used in oil and natural gas refining and processing facilities, one third of the H_2S is first oxidized to SO_2 in a furnace. The SO_2 and the remaining H_2S then reacts in the furnace and in a series of reactors to produce elemental sulfur. The overall removal efficiency of a Claus Process is dependent on the number of catalytic reactors installed [5, 6, 7].

The first commercial liquid oxidation process is the Stretford Process, which uses an aqueous solution of sodium carbonate, sodium bicarbonate and anthraquinone disulfonic acid to dissolve oxygen in the aqueous solution in order to oxidize the H_2S to sulfur. The reaction rate is slow. Consequently, alkali vanadates are added to the solution to promote the oxidation. Since vanadium is toxic, the main drawback to the Stretford Process is that the process must be designed to handle the sulfur cake, and the discharge solution [8]. The Stretford Process is modified to avoid the generation of toxic waste by using chelated iron to promote the reaction between H_2S and dissolved oxygen. Following the absorption of H_2S into water and its subsequent ionization, sulfide anions are oxidized to elemental sulfur. The accompanying reaction is the reduction of ferric ions to ferrous ions.

Adsorption for the removal of trace amounts of pollutants has been in practice for years. For removing H_2S from gas streams, activated carbon is the preferred adsorbent due to its high capacity [9, 10]. There is evidence that, in the presence of oxygen, activated carbon adsorbs H_2S and catalyzes the oxidation of the gas [11, 12]. Generally, activated carbon is used only for removing H_2S from air streams, since the carbon would non-selectively adsorb most of the components present in an anaerobic stream.

Caustic absorption systems are usually grouped with chemical oxidation systems. However, the caustic absorption reaction is an equilibrium limited process while chemical oxidation processes in general are not. In a caustic absorption system, the solution is maintained at a high pH to enhance the absorption of H_2S. To control the salt content of the scrubbing solution, a portion is discharged from the system. If the pH of the spent scrubbing solution is allowed to decrease by mixing it with other waste streams, the reaction is driven back and H_2S is released to the atmosphere. This is the reason that the spent scrubbing solutions are classified as hazardous substances [13, 14].

Odor control in wastewater treatment plants is generally accomplished by absorbing the malodorous compounds into aqueous solution and then chemically oxidizing them to innocuous, odorless compounds. Although there are a variety of chemical oxidants available, such as chlorine (Cl_2), ozone (O_3), sodium hypochlorite (NaOCl), potassium permanganate ($KMnO_4$), hydrogen peroxide (H_2O_2) and ferric salt (Fe^{3+}), the most frequently used is a combination of sodium hydroxide (NaOH) and sodium hypochlorite [15, 16, 17, 18]because they are relatively inexpensive, readily available, and have a high oxidizing capacity. In this process, all of the reactions occur in the aqueous phase in which the chemical oxidants are dissolved. Consequently, the gaseous, odorous components must contact the aqueous solution in a way that the odor components will dissolve. Although countercurrent packed bed scrubbers are the most common configuration, spray towers, ejector venturi scrubbers, plate columns, mist scrubbers and even mobile-bed absorbers are used in this application [19, 20, 21, 22, 23, 24]. Odor control systems in wastewater treatment plants are designed to remove not only H_2S but also other odorous components. The design is usually based on an overall odor intensity.

A pilot plant program was initiated to test solutions of NaOH/NaOCl for their ability to absorb H_2S in a packed bed scrubber. The objective of this research was to study H_2S as single target compound to obtain operating conditions and design parameters for precise scrubber design.

THE CHEMISTRY

The actual absorption/oxidation reactions are quite complex, however they can be represented by:

$$H_2S_{(g)} + NaOH_{(aq)} \leftrightarrow Na_2S_{(aq)} + 2H_2O_{(l)} \qquad (1)$$

$$Na_2S_{(aq)} + 4NaOCl_{(aq)} \rightarrow Na_2SO_{4(aq)} + 4NaCl_{(aq)} \qquad (2)$$

Equation 1 illustrates the reaction in a caustic absorption system. The reaction is driven to the right as the pH of the solution increases, i.e., as more caustic is added, and to the left as the pH is decreased. When the pH of the spent scrubbing solution is allowed to decrease, H_2S will be released. The scenario may create an odor problem or, even worse, a hazardous condition. This is because the reaction in Equation 1 is reversible. To prevent this from occurring, NaOCl is added to provide an irreversible reaction, as illustrated in Equation 2. Byproducts of the chemical oxidation are water soluble and will accumulate in the scrubbing solution until it becomes saturated and salt precipitation occurs. As shown in these equations, NaOH and NaOCl are continuously consumed. This represents an operating cost that is directly proportional to the amount of H_2S being removed.

CHEMICAL ABSORPTION IN A PACKED BED

Consider a packed bed with the following characteristics. The cross section is Ω and the differential volume in height dZ is ΩdZ. If the change in molar flow rate F is neglected, the amount absorbed in section dZ is $-Fdy$, which is equal to the absorption rate times the differential volume:

$$-Fdy = K_y a\,(y-y^*)\,\Omega dZ \qquad (3)$$

This equation is rearranged for integration by grouping the constant factors F, ΩdZ, and $K_y a$ with dZ.

$$\frac{K_y a\Omega}{F}\int_0^{Z_T} dZ = \frac{K_y a\Omega Z_T}{F} = \int_b^a \frac{dy}{y-y} \qquad (4)$$

The equation for the column height can be written as follows:

$$Z_T = \left[\frac{\left(\frac{F}{\Omega}\right)}{K_y a}\right]\int_b^a \frac{dy}{y-y} \qquad (5)$$

The integral in Equation 5 represents the change in gas phase concentration divided by the average driving force and is defined as the number of transfer units, NTU. The other part of Equation 5 has the unit of length and is called the height of a transfer unit, HTU.

The chemical reaction in the liquid phase reduces the equilibrium partial pressure of the solute over the solution, which greatly increases the driving force for mass transfer. If the reaction is essentially irreversible at absorption conditions, the equilibrium partial pressure is zero, and the NTU can be calculated just from the change in gas composition [25], where y* = 0.

$$NTU = \int_b^a \frac{dy}{y} = \ln\left(\frac{y_a}{y_b}\right) \qquad (6)$$

A part of the research described in this paper is directed at obtaining the HTU for H_2S absorption in an NaOCl caustic aqueous solution.

EXPERIMENTAL SECTION

The pilot plant scrubber consists of a gas blending system, a gas scrubber, a chemical injection and control system and an H_2S monitoring unit. Figure 1 is a schematic of the pilot plant. The gas blending system is capable of producing a wide variety of gas compositions by mixing air with high concentration H_2S from cylinders. The H_2S-containing air stream is then passed through the scrubbing tower where H_2S is absorbed and oxidized. Samples are taken from the inlet streams and effluents to determine the removal efficiency of H_2S and, through calculation, HTU.

Apparatus

The gas blending system is capable of total flow rates of 45 m^3/min (1600 cubic feet per minute, cfm). The H_2S concentrations are regulated by injecting it from a 5% gas cylinder to the air stream. The whole system is made of glass fiber reinforced plastic (FRP), including the blower, except for the H_2S injection lines that are polypropylene tubing. After the H_2S is injected into the air stream, the whole stream is passed into a section of Tellerete Packings to achieve better mixing. The well mixed H_2S-containing air stream is then carried into the gas scrubber where absorption and chemical reaction occur.

The packed bed scrubber is constructed of a 5 meter tall and 0.45 meter diameter polypropylene column with a 1.8 meter packed bed section randomly packed with 3.25 inch, No. 2 K-type Tellerete Packings. The top of the column holds a demister head packed with No. 1 R-type Tellerete Packings for removing entrained droplets from the gas stream. The entire column sits on top of a vessel which serves as the scrubbing solution reservoir.

The concentrations of NaOH and NaOCl in the scrubbing solutions are monitored and controlled by a system of pH meter/metering pump, and oxidation reduction potential (ORP) meter/metering pump, respectively. A circulating pump withdraws scrubbing solution from the reservoir and pumps it up to the top to be sprayed down on the packed bed, countercurrent to the gas flow. The rough pumping rate is controlled by regulating the recirculating rate, with the final adjustment being made at the Signet 5500 flow meter downstream from the pump.

Analysis

A Multi Rae PGM-50 H_2S analyzer is used to measure the inlet and outlet concentrations of H_2S. The instrument utilizes the principle of UV photo ionization for detection and measurement of gas phase H_2S. During a normal operation, a continuous sample is drawn into the detector chamber by an internal pumping system. The sample stream is metered and passed through the particle filters before reaching the detector chamber, where the sample is exposed to UV light, which ionizes the H_2S. An electric field drives ions to collect electrodes, and generates a current corresponding to the collection rate. An electrometer preamplifier is used to measure the current, and then sends the signal to an external LCD display. The H_2S analyzer used in this research has a detection range of 0 to 300 ppm with a resolution of 0.1 ppm.

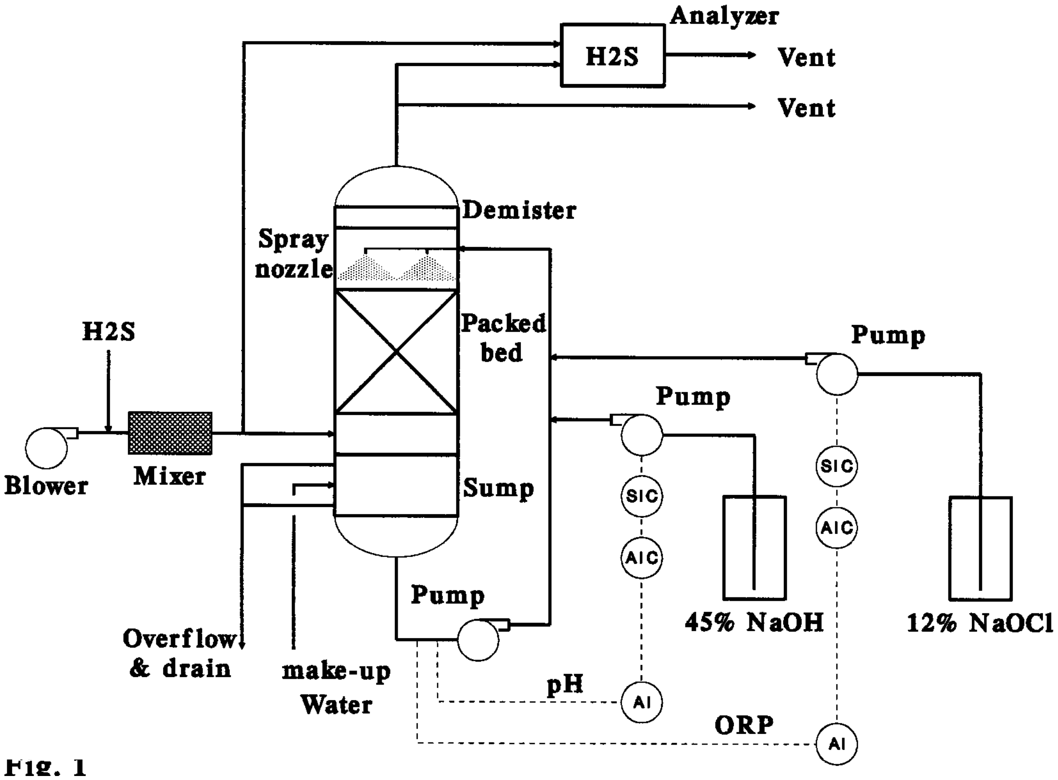

Figure 1. The schematic of the pilot plant gas scrubbing system.

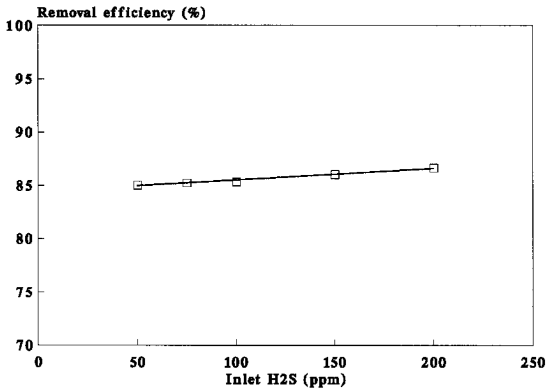

Figure 2. The effect of inlet concentration on H_2S absorption in a packed bed scrubber.

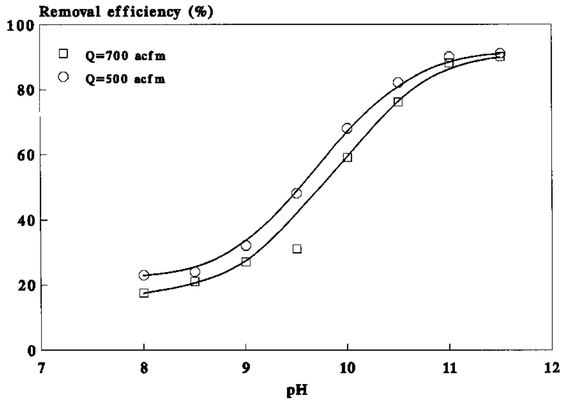

Figure 3. The effect of NaOH on H_2S absorption with gas flow rates at 500 cfm and 700 cfm, and liquid mass flow rate at 2,000 lb/ft^2 hr.

Table 1. Experimental parameters.

	Scrubber parameters	
Column diameter (ID)	m	0.45
Tower height	m	5
Packing height	m	1.8
Packing size (nominal)	in	3.25
	Gas parameters	
Gas flow rate (standard)	ft^3/min, cfm	600
Gas mass flow rate	lb/ft^2 hr	1,500
Gas temperature (room)	°C	25
Gas composition (H_2S/air)	ppm	200
	Liquid parameters	
Liquid mass flow rate	lb/ft^2 hr	2,000
Alkalinity (by NaOH)	pH	11
ORP (by NaOCl)	mV	450

RESULTS AND DISCUSSION

Parameters such as H_2S inlet concentrations, NaOH and NaOCl concentrations in the scrubbing solutions, as well as gas and liquid flow rates were studied for their effect on H_2S removal. A range of operating conditions were established after these tests, and the height of a transfer unit (HTU) was found to correlate to gas flow rate. This correlation should be studied further before designing the full-scale scrubber.

Hydrogen Sulfide

A limited number of experiments were performed at the conditions indicated in Table 1. The H_2S concentration was varied from 50 to 200 ppm. The actual measurements from these experiments are plotted in Figure 2. The data indicate that H_2S is effectively absorbed in the NaOH aqueous solution. However, the removal efficiency seems to be independent of the inlet concentrations of H_2S in the range of 50 to 200 ppm.

Sodium Hydroxide

A set of experiments were carried out with the pH held between 8 and 11.5 to determine its effect on H_2S removal. The pH was controlled by pumping 45% NaOH aqueous solution into the NaOCl-containing scrubbing solution. The results of these runs are given in Figure 3. The H_2S removal efficiency increased from 20% to 90% while the pH was increased from 8 to 11.5. The experiments were repeated at a higher gas flow rate. As expected, the H_2S removal efficiency at a flow rate of 700 cfm was about 7% lower than that at 500 cfm. Apparently, this is due to the shorter residence time in the scrubber.

In view of these results, it was decided to increase the liquid rate to further reduce the outlet concentration of H_2S. The liquid rate was adjusted from 2000 lb/ft^2 hr to 3000 lb/ft^2 hr. Figure 4 shows the differences of H_2S removal between these two runs. A 10% increase in removal efficiency was demonstrated across the whole range of pH from 8 to 12.

Sodium Hypochlorite

A set of runs were made under conditions identical to those described in the previous section, except the concentrations of NaOCl in the scrubbing solution were adjusted to have ORPs of between 350 and 500 millivolts (mV). The ORPs were used to monitor and

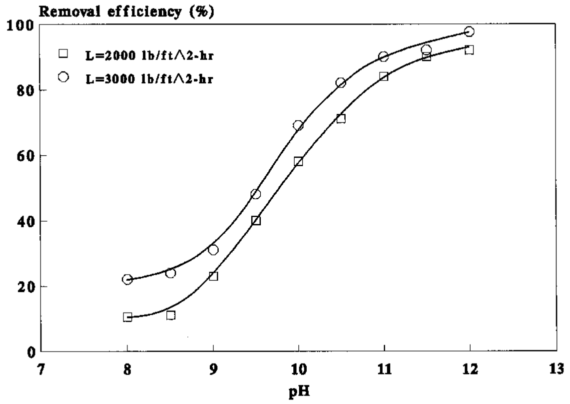

Figure 4. The effect of NaOH on H_2S absorption with liquid mass flow rates at 2,000 lb/ft^2 hr and 3,000 lb/ft^2 hr.

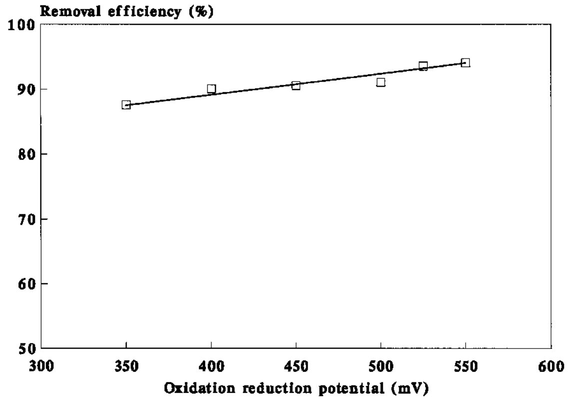

Figure 5. The effect of NaOCl on H_2S absorption in caustic aqueous scrubbing.

control the concentration of NaOCl in the scrubbing solution. The effect of ORP on H_2S removal are given in Figure 5. The H_2S removal efficiency increases from 87% to 93% with respect to an ORP increase from 350 mV to 500 mV. A slight enhancement of H_2S removal might have been due to the oxidation of sulfide ions by the NaOCl in the scrubbing solution.

When dissolved in water, NaOCl forms chlorine (Cl_2), hypochlorous acid (HOCl) and hypochlorite ions (OCl^-) in the solution. White [26] provides equilibrium data to determine the proportions of each component as a function of pH. The presence of HOCl and OCl^- were confirmed by continuous monitoring with a UV-range photodiode detector in a previous study [27]. Figure 6 shows the equilibrium concentrations of Cl_2, HOCl and OCl- in the scrubbing solution, and the scrubber's H_2S removal efficiency. At pH between 8.5 and 11.5, concentrations of the oxychlorine compounds were unchanged, while H_2S removal increased from 10% to 90% with the increase of alkalinity. Apparently, none of the oxychlorine compounds are the active ingredient in this process. This is why the reaction in Equation 1 is proposed to be the rate determining step of this process.

Liquid Gas Ratio

A number of experiments were carried out at the conditions described in Table 1 with NaOCl concentrations of 0.003 and 0.006 molar (M). The gas flow rate was varied from 300 to 900 ft^3/min. The liquid rate was held constant at 3000 lb/ft^2 hr. Thus, the practical range of 1.25 to 3.75 liquid-to-gas mass ratio (L/G) was studied. The actual measurements from these experiments are plotted in Figure 7. The data indicate that the effectiveness of H_2S removal was almost constant with L/G. A minimum L/G of 1.5 was needed to have a stable H_2S removal. Figure 7 also shows a minimal difference of H_2S removal between the scrubbing solutions with different NaOCl concentrations.

Two sets of experiments were run to determine the effect of L/G on H_2S removal at pH 10.5 and 11. The results from these runs are plotted in Figure 8. The results indicate that H_2S is absorbed more effectively in solutions with high pH. The scrubbing effectiveness of H_2S was sensitive to the L/G ratio only when pH was low. There was a 10% to 20% difference in H_2S removal between the scrubbings at pH 10.5 and pH 11. It thus became apparent that only NaOH was the active ingredient in this scrubbing process.

Gas Flow Rate

The liquid-gas mass ratio is the most important parameter for the design of an absorption tower. Thus, for a given gas flow, a reduction in liquid flow decreases the slope of the operating line. This, however, is not the case for chemical absorption. In a chemical scrubber, H_2S is continuously removed by its reaction with NaOH and NaOCl. Therefore, no H_2S accumulates in the scrubbing solution, as stated in Equation 6. As long as a scrubbing solution is provided to cover a reasonable portion of the interfacial area of the packings in the scrubber, liquid flow rate demonstrates a minimal effect on absorption efficiency. However, because H_2S removal is accomplished by chemical reactions, residence time is an important consideration. Thus, gas flow rate is expected to play a significant role in this process.

A set of experiments was performed to determine absorption rates of H_2S in NaOH/NaOCl aqueous scrubbing. The gas flow rate was varied from 300 cfm to 900 cfm. Table 2 shows the result of reducing outlet concentration of H_2S by increasing NaOCl to 0.2 M and liquid rate to 3,000 lb/ft^2 hr. A 99.2% removal rate was achieved. The absorption rate in terms of HTU was calculated by plugging the packing height, and inlet and outlet concentrations of H_2S into Equation 6.

The next set of experiments was designed to correlate HTU to gas flow rate. The experiments were performed at the conditions indicated in Table 1 with the pH of 11 and 12. Figure 9 shows the HTU as a function of gas flow rate. Theoretically, HTU is linear to gas flow rate. The slopes of the HTU plots decrease in the loading region because of the increase in interfacial area. Figure 10 shows the same trend of the dependency of HTU on gas flow rate as NaOCl concentrations varies. Apparently, the effect of pH on HTU is significant while the effect of NaOCl concentration on HTU is minimal.

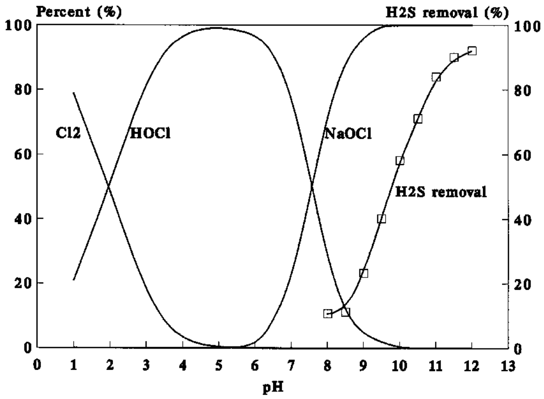

Figure 6. Equilibrium concentrations of Cl_2, HOCl and OCl^-, and absorption efficiency of H_2S as a function of pH in the scrubbing solution.

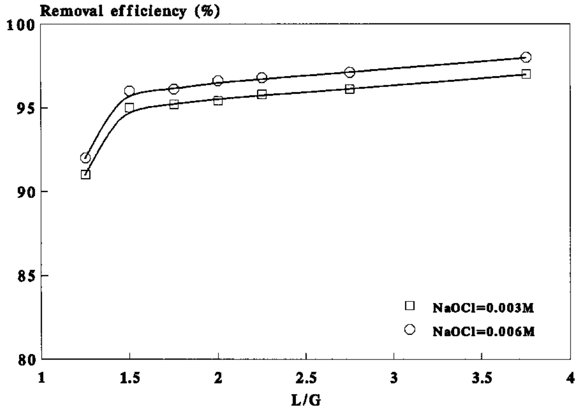

Figure 7. The effect of liquid-gas mass ratio on H_2S absorption at NaOCl concentrations of 0.003 and 0.006 molar.

Table 2. Height of a transfer unit.

Gas mass rate (lb/ft^2 hr)	L/G	H_2S inlet (ppm)	H_2S outlet (ppm)	Removal (%)	HTU (ft)
790	5.06	199	1.7	99.2	1.24
1053	3.8	198	2.3	98.8	1.33
1316	3.04	198	2.8	98.6	1.39
1579	2.53	197	3.2	98.4	1.43
1842	2.17	199	3.9	98.0	1.50
2105	1.9	196	4.7	97.6	1.58
2369	1.69	195	9.6	95.1	1.96

CONCLUSIONS

The NaOH aqueous solution is effective for H_2S removal in a packed bed scrubber. A 99.2% removal rate is achievable at a reasonable gas flow rate. The existence of NaOCl creates an irreversible reaction to prevent H_2S from accumulating in the solution and/or from being released to the atmosphere.

The NaOH is the only chemical parameter which significantly affects the removal of H_2S from air streams. The enhancement effect may be due to high pH rather than specifically to NaOH. An alkalinity of pH 11 is essential to have an HTU in the range of one to two feet for a gas flow rate between 700 lb/ft^2 hr to 2,100 lb/ft^2 hr.

As predicted by Equation 6, gas flow rate is the only physical parameter which strongly influences the HTU. The slopes of the HTU plots decrease in the loading region because of the increase in interfacial area.

The ORP can be used to monitor and control the concentration of NaOCl in the scrubbing solution. Since the NaOCl does not react with H_2S directly, it makes no sense to operate the scrubbing system at high ORP. An ORP of 450 mV is adequate for a 99% removal, provided a pH of 12 is maintained.

ACKNOWLEDGMENT

The authors are grateful to Arthur Lee, President of Kunstoff Manufacturer Company, for support of this research.

LITERATURE CITED

1. National Institute for Occupational Safety and Health, *NIOSH Pocket Guide to Chemical Hazards*, DHHS publication 85-114, 1987.
2. **Kohl, A. and F. Riesenfeld**, *Gas Purification, 4th Edition*, Gulf Publishing, Houston, TX, 1985.
3. **Rafson, H.**, Editor, *Odor and VOC Control Handbook*, McGraw-Hill, New York, NY, 1996.
4. **Kohl, A. and F. Riesenfeld**, "Alkanolamines for Hydrogen Sulfide and Carbon Dioxide Removal," Chapter 2, *Gas Purification, 4th Edition*, Gulf Publishing, Houston, TX, 1985.
5. **Kohl, A. and F. Riesenfeld**, "Dry Oxidation Processes for Hydrogen Sulfide Removal," Chapter 8, *Gas Purification, 4th Edition*, Gulf Publishing, Houston, TX, 1985.
6. **Nedez, C. and J. Ray**, "A New Claus Catalyst to Reduce Atmospheric Pollution," *Catalysis Today*, 27, 1996.
7. **Suppiah, S. and D. Burns**, "Hydrogen Sulfide Oxidation Over Teflon Treated Activated Alumina and Titanium Dioxide Catalysts," *Can. J. Chem. Eng.*, 71, 1993.
8. **Kohl, A. and F. Riesenfeld**, "Liquid Phase Oxidation Processes for Hydrogen Sulfide Removal," Chapter 9, *Gas Purification, 4th Edition*, Gulf Publishing, Houston, TX, 1985.
9. **Lever, J.P. and D.J. Jefferies**, "Vapor Phase Filtration Using Activated Carbon," *Filtration and Separation*, 10, pp 707, 1993.

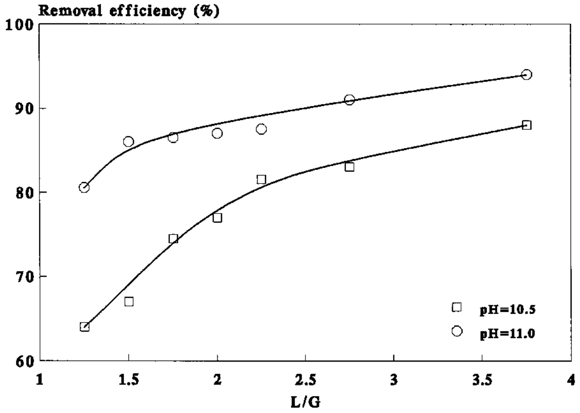

Figure 8. The effect of liquid-gas mass ratio on H_2S absorption at alkalinity of pH 10.5 and 11.

10. **Meeyoo, V., D. Trimm, and N. Cant**, "Adsorption-Reaction Processes for the Removal of Hydrogen Sulfide from Gas Streams," *J. Chem. Tech. Biotechnol.*, 68, pp 411-416, 1997.
11. **Ghosh, T.K. and E.L. Tollefson**, "Kinetics and Mechanism of Hydrogen Sulfide Over Activated Carbon in the Temperature Range of 125-200° C," *Can. J. Chem. Eng.*, 64, pp 969, 1986.
12. **Klein, J. and K. Henning**, "Catalytic Oxidation of Hydrogen Sulfide on Activated Carbons," *Fuel*, 63, p 1064, 1984.
13. Water Environmental Federation and American Society of Civil Engineers, "Odor Control in Wastewater Treatment Plants," *WEF MOP 22, ASCE Manuals and Reports on Engineering Practice*, 82, 1995.
14. American Water Works Association, "AWWA Standard for Caustic Soda," ANSI/AWWA B501-88, Denver, CO, 1988.
15. **Bonanni, E.**, "The Addition of Chemicals to Liquid to Control Odors," Section 8.1, *Odor and VOC Control Handbook*, H. Rafson, Editor, McGraw-Hill, New York, NY, 1996.
16. American Water Works Association, "AWWA Standard for Ferrous Sulfate," ANSI/AWWA B402-90, Denver, CO, 1990.
17. American Water Works Association, "AWWA Standard for Hypochlorites," ANSI/AWWA B300-87, Denver, CO, 1987.
18. American Water Works Association, "AWWA Standard for Liquid Chlorine," ANSI/AWWA B301-92, Denver, CO, 1992.
19. **Bowker, R.**, "Chemical Scrubbing: Other Designs," Section 8.6.3, *Odor and VOC Control Handbook*, H. Rafson, Editor, McGraw-Hill, New York, NY, 1996.
20. **Rafson, H.**, "Mist Scrubbing Technology, Recent Development and Current Practices in Odor Regulations, Control and Technology," *Transactions Air and Waste Management Association*, October 1989.
21. **Waltrip, D. and E. Snyder**, "Elimination of Odor at Six Major Wastewater Treatment Plants," *J. WPCA*, 57, 10, pp 1027-1032, October 1995.

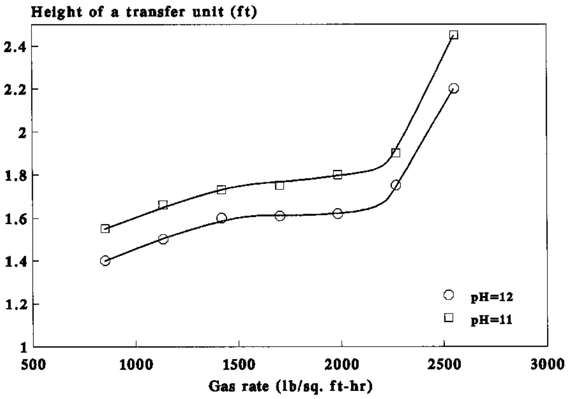

Figure 9. The effect of gas mass flow rate on HTU for H_2S absorption in a packed bed scrubber at alkalinity of pH 11 and 12.

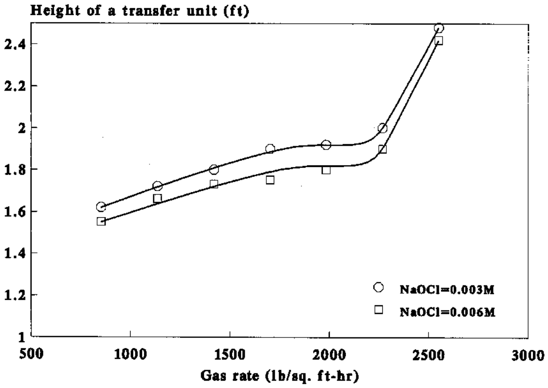

Figure 10. The effect of gas mass flow rate on HTU for H_2S absorption in a packed bed scrubber at NaOCl concentrations of 0.003 and 0.006 molar.

22. **Stitt, E.H. and M.E. Fakley**, "New Process for the Abatement of Odorous and Low Level VOCs," AIChE Spring National Meeting, Houston, TX, March 20, 1996.
23. **Stitt, E.H., K. Kelly, A.R. Elgood, and M.E. Fakley**, "Guarding Against Odors," *Environmental Protection*, January 1996.
24. **Nagl, G.**, "Case History: Odor Control at a Water Treatment Plant," *National Environmental Journal*, March/April 1996.
25. **McCabe, W., J. Smith, and P. Harriott**, *Unit Operations of Chemical Engineering, 4th Edition*, McGraw-Hill, New York, NY, 1985.
26. **White, G.C.**, *The Handbook of Water Chlorination, 2nd Edition*, Van Nostrand Reinhold Co., New York, NY, 1986.
27. **Yang, C.-L.**, "Aqueous Absorption of Nitrogen Oxides Induced by Oxychlorine Compounds: A Process Development Study for Flue Gas Treatment," Doctoral thesis, New Jersey Institute of Technology, 1994.