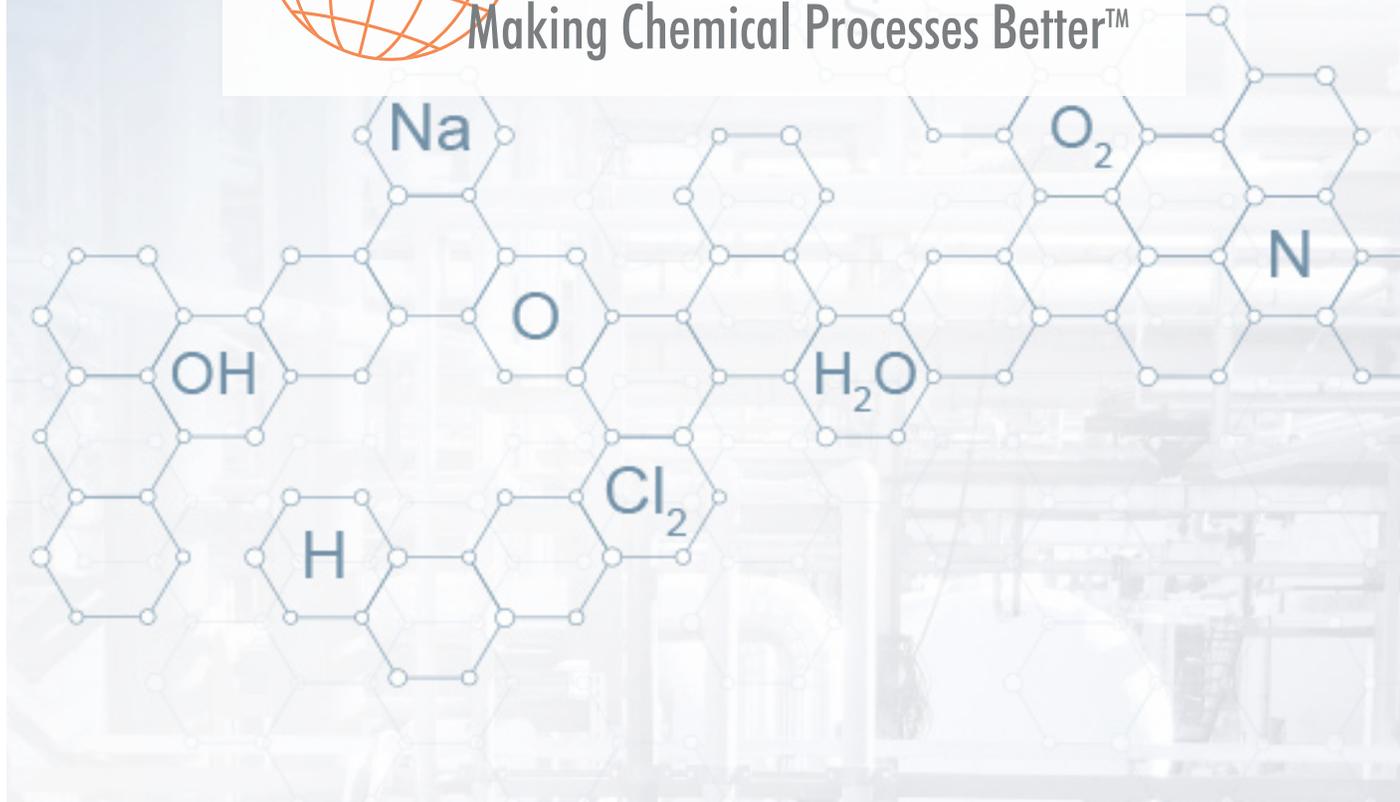




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CHLORINE STACK EMISSIONS FOR THE SENTRY 2000

US Patent # 5, 393, 314



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CALCULATION

The Sentry 2000 is a patented horizontal cross flow packed bed scrubber system with major applications in chlorine and sulfur dioxide emissions control. These systems have been installed for the emergency scrubbing of chlorine and sulfur dioxide container rooms should leakage of the containers or piping systems occur.

The major design criterion applied to scrubber systems is the stack discharge concentration during emergency operation. This concentration is specified by the Uniform Fire Code (UFC) not to exceed one half of the immediately dangerous to life and health (IDLH) level of a toxic gas. From the late 1980's to 1995 the IDLH level, expressed in parts per million (PPM), had been set at 30 PPM for chlorine. During 1995, however, the chlorine IDLH level was changed to 10 PPM.

In 1993, we in conjunction with Mr. Ralph Strigle, a world-recognized expert in packed tower scrubber systems, designed the Sentry 2000 to neutralize chlorine and sulfur dioxide. Based on mass transfer efficiency calculations, the Sentry 2000 system utilized packed bed technology developed over more than 50 years. Mass transfer efficiency calculations for packed beds have proven to be accurate when compared to actual systems. Additionally, results for packed beds, unlike spray chambers or venturi scrubbers, can be scaled upwards or downwards reliably. Enclosed is a technical paper by Mr. Strigle presenting the calculations used to predict and corroborate the performance of the Sentry 2000. System performance is verified using two independent methods consisting of mass transfer driving forces with inlet and outlet concentrations.

The Sentry 2000 was designed to operate at an inlet flow rate of 3,000 ACFM for contaminant release rates in excess of 78 lbs/min. This leakage rate is specified by the UFC and represents an overfilled one ton chlorine or sulfur dioxide cylinder emptying in 30 minutes. The design was originally based on the 1993 IDLH of 30 PPM for chlorine and 100 PPM for sulfur dioxide but is easily adaptable to reduced IDLH levels.

Sentry 2000 Design Evaluation

Full scale testing was carried out to verify the design and demonstrate the performance of this scrubber system for emergency operation. The Sentry 2000 was successfully tested in 1993, achieving chlorine discharge levels of less than 5 PPM for a 3,000 ACFM inlet gas flow. Tests were conducted with full one ton releases of chlorine at leakage rates in excess of 78 lbs/min throughout the entire release periods. For these tests, a caustic flow rate of 400 gallons per minute (GPM) was selected for chlorine neutralization based on Mr. Strigle's calculations using the 1993 UFC 15 PPM outlet stack limit.

Due to the importance of accurate test procedures, Entropy, Inc., the largest gas testing company in the industry, was contracted to conduct the performance evaluation of the Sentry 2000. Dr. John Richards of Entropy, a nationally recognized chemical engineer specializing in air pollution control equipment, was on-site and in charge of all data collection using EPA referenced test methods (EPA Method 26). These referenced test methods are the only means of chlorine emissions testing recognized by the EPA.

In addition to the EPA reference test methods, Dräger test tubes and a continuous electronic monitor were utilized during testing of the Sentry 2000. The EPA test methods provided average stack discharge concentrations and these data were used for performance review. Dräger test tubes provided an immediate check of the system performance. The continuous monitor provided an indication of the outlet

concentration trends but was not used to provide quantitative chlorine levels. As detailed in the letter located in the appendix by Dr. John Richards of Air Control Techniques, P.C., currently there is not EPA approved performance specification test for chlorine electrochemical sensors nor is there any work in progress to develop one. In addition, the letter located in the appendix by Mr. Phillip Juneau of Emission Monitoring, Inc., states that continuous chlorine sensors can suffer from calibration drift, non-linearity and temperature effects that produce erroneous results. According to Mr. Juneau, EPA validation tests have not been conducted successfully for continuous electrochemical chlorine sensors and thus the EPA does not recognize them as acceptable chlorine measurement systems.

The continuous chlorine monitor, while not suitable for absolute chlorine concentration measurements, does provide a relative indication of changes in concentration. This indication of concentration change allows for the stimulation of peak chlorine levels relative to the average chlorine concentrations provided by the EPA Method 26 results. Addition of the difference between peak and average continuous monitor reading the EPA Method 26 provides an estimate of peak concentrations during the chlorine release period.

Test Results

Tests of the scrubber system were conducted on August 11 and 12, 1993. Two chlorine releases were conducted with release rates above the 78 lbs/min specification. The tests were observed by Airflow Sciences Corporation (ASC), an independent engineering firm specializing in numerical fluid flow simulation, and the results were documented in ASC report number R-93-020.

The first test of the scrubber system was a 2,000 lb chlorine release with an initial leakage rate of 120 lbs/min. This leakage rate resulted in an inlet chlorine concentration of 193,400 PPM as opposed to the 130,000 PPM expected for a 78 lbs/min release, an increase of 150% over the chlorine flow rate in the UFC specification. The gas flow rate of the unit was measured at 3,094 ACFM with a caustic flow of approximately 400 GPM. The average chlorine flow rate for the test was 88.4 lbs/min and did not drop below 80 lbs/min throughout the release period.

Dräger measurements taken at the beginning of the test peaked at a chlorine concentration of 3 PPM with an average of approximately 2.5 PPM. The EPA reference method test indicated an average chlorine concentration of 3.63 PPM in the outlet stack during the chlorine release period. The continuous monitor showed a peak value approximately 0.5 PPM higher than its average reading during the release period. Adding this 0.5 PPM to the EPA Method 26 average of 3.63 PPM gives an estimated peak of 4.1 PPM. This peak value is well below both the 1993 UFC limit of 15 PPM and the 1995 maximum of 5 PPM even though initial chlorine concentrations exceeded design specifications by 150%.

A second chlorine neutralization test was conducted at an initial release rate of 140 lbs/min. This resulted in an initial chlorine concentration of 231,500 PPM, a 180% increase over the design specifications. The gas flow rate of the unit was measured at 3,024 ACFM with a caustic recirculation rate of approximately 400 GPM. The average chlorine flow rate for this test was 90.8 lbs/min and did not drop below 84 lbs/min during the release period.

Dräger measurements during the release period indicated an average chlorine concentration of about 3.5 PPM with a peak of 5 PPM. The EPA reference method test indicated an average chlorine concentration of 5.08 PPM in the outlet stack during the release. The continuous monitor indicated a peak value 2 PPM higher than the release period average. This value when added to the EPA reference method average of 5.08 PPM gives an estimated peak concentration of 7.1 PPM. The peak value is well below the 1993 UFC maximum and is only slightly above the 1995 limit of 5 PPM, despite initial chlorine concentrations 180% higher than design specifications.

As mentioned previously, the caustic recirculation rate had been selected based on a goal outlet chlorine concentration of 15 PPM. As indicated by Mr. Strigle's calculations, the only change to the system required for designing below the 5 PPM limit would be an increase in the caustic flow rate to 520 GPM instead of the 400 GPM used during testing. Based on the EPA test method results the Sentry 2000 system did not exceed the 1995 UFC limit of 5 PPM on the first chlorine test with initial inlet concentrations 150% above design specifications. In addition, the scrubber system would not have exceeded 5 PPM during the second test (where the initial flow rate of chlorine was 180% over design specifications) if the caustic recirculation rate had been increased to 520 GPM.

Summary

The Sentry 2000 was designed to neutralized chlorine and sulfur dioxide and has been thoroughly evaluated in a rigorous test program. Prior to this testing in 1993, no manufacturer had tested at an air flow rate of 3,000 ACFM and contaminant leakage rates exceeding 78 lbs/min for the entire release period. Test results correlated very well with Mr. Strigle's predicted mass transfer efficiencies giving further proof of the validity of the calculations. This close agreement between predicted and actual results also provides additional confidence in the ability to use the equations for packed beds to accurately scale results of different flow rate. The test results and mass transfer efficiency calculations indicated that the Sentry 2000 will meet or exceed performance levels specified by the Uniform Fire Code.

It has been reported that another manufacturer has conducted testing of a chlorine scrubber system. The claims of this manufacturer, however, are not comparable to the Sentry 2000 test results for several reasons. The manufacturer's test was conducted at 1,180 ACFM with only 550 lbs of chlorine released at a leakage rate that dropped below 78 lbs/min during the release period. In addition, this manufacturer's test results were obtained using a continuous chlorine monitor as opposed to following EPA Test Method 26.

Gas flow rate has an important effect on outlet concentrations. For example, if the packed bed design of the Sentry 2000 had been tested at 1,500 ACFM instead of 3,000 ACFM the calculated chlorine concentration at the outlet would have dropped to 0.55 PPM for a 400 GPM caustic flow rate. With a 500 GPM caustic recirculation rate at 1,500 ACFM, the outlet chlorine concentration would have been 0.26 PPM. These calculations indicate that testing at a lower airflow rate can lead to significantly lower outlet chlorine concentrations. While results for the Sentry 2000 can be scaled up or down using the mass transfer calculations for packed beds, results from other manufacturer's test cannot be scaled because their system contains a spray chamber.

Allowing the chlorine leakage rate to fall below 78 lbs/min in addition to a lower release weight (550 lbs versus 2,000 lbs) put considerably less strain on a scrubber system. The manufacturer who conducted this test initially had a release rate above 78 lbs/min but allowed it to drop below this rate after a few minutes. This reduced leakage rate combined with the lower release weight will obviously result in lower concentrations at the outlet, but compliance with the UFC standards cannot be inferred from these results.

Finally, the use of a continuous chlorine monitor can provide a relative reading with respect to high and low concentrations, but cannot measure quantitative chlorine levels accurately.

The only approved means of chlorine measurements is through the implementation of EPA Method 26 as was utilized in the testing of the Sentry 2000.

Tests have shown that the patented Sentry 2000 design provides discharge chlorine concentrations of less than 5 PPM for a gas flow rate of 3,000 ACFM, even when chlorine leakage rates exceed design specifications by 150%. Increasing the caustic recycle rate of the scrubber, based on calculations for inlet and outlet concentrations, will allow guaranteed system performance at even higher chlorine inlet levels. Therefore, the Sentry 2000 can meet current chlorine outlet concentrations required in any specification.

Please refer to the enclosed technical paper with accompanying calculation for details on the Sentry 2000 performance.

Evaluation of Design

Fume scrubbers remove contaminants from an airstream by intimate contact between a scrubbing liquid, which is dispersed to provide a large surface area, and a turbulently flowing gas stream. For contaminants which are soluble in the scrubbing liquid, the removal takes place by absorption of the contaminant. Spray chambers, Venturi scrubbers, and packed towers can be used to accomplish this absorption.

Gas/liquid interfacial surface area can be produced by use of spray nozzles that disperse the liquid. The size, and therefore the surface area, of the liquid droplets formed depend on the flow rate, pressure drop, and design of the spray nozzles. The arrangement and size of the spray nozzles also determine the interfacial area available per cubic foot of scrubber volume. Tests conducted by an independent, international research organization have demonstrated that uniform gas/liquid contact could be achieved only by use of a double-overlapping spray pattern. Therefore, the usual configurations of sprays are not recommended for mass transfer operations. In addition, the number of transfer units developed does not increase in direct proportion to the height of a spray column (Perry's Chemical Engineers Handbook). This presents a problem for scale-up.

Venturi scrubbers can rely on the gas-phase energy to produce interfacial area for gas/liquid contact. Thus, generation of a large liquid surface area requires a high pressure drop in the gas stream. Alternately, jet scrubbers can aspirate the gas phase by use of a high liquid flow delivered at high pressure. The performance of such units is unique for each size and design. With either type of scrubber, there is a large power requirement. Since the gas/liquid contact time is short, the number of transfer units achieved by these devices is limited (Perry's Chemical Engineers Handbook).

Packed towers are the most common device for pollution control applications. ("Handbook, Control Technologies for Hazardous Air Pollutants", U.S. EPA) Packed towers provided a large wetted surface area for absorption. All of the surface area of the packing is available as long as the minimum liquid flow needed is uniformly applied to the packed bed. Further, the mass transfer efficiency of packed beds can be predicted reliably from technology developed over more than 50 years. Also, packed scrubbers have low power requirements and are adaptable easily to corrosion-resistant construction.

Because of the advantage of packed towers, this type was selected for the patented Sentry 2000 Scrubber. A 4-pass, cross-flow scrubber was selected to provide the amount of tower packing required to absorb the chlorine present in 3000 ACFM of gas from a 78 lb/min liquid chlorine discharge with less than 15 ppm of contaminant in the vented gas stream.

Such a design, with horizontal gas flow and vertical liquid flow, produces a compact unit that occupies a minimum of space. A modern plastic packing is used that provides high mass transfer efficiency and low pressure drop.

The use of little orifices in spray nozzles in order to produce smaller liquid droplets increased the possibility of nozzle plugging. Obviously a fouled nozzle provides a path for gas flow without liquid contact of solute absorption. So as to avoid this type of operating difficulty, the Sentry 2000 Scrubber is equipped with liquid distributor pipes which contain bigger orifices. A large number of these orifices uniformly located insure an even liquid distribution onto the packing. These big orifices operate at a low pressure drop thus avoiding a hazard presented by use of high pressure caustic piping. Further, the liquid is fed to the packed bed at a low velocity which promotes lateral spreading and uniform wetting of the packing surfaces. A series of baffles extend from the top of the scrubber down into the packed bed to prevent any bypassing of gas stream around the distributor pipes. The liquid sump is designed to contain 1.5 times the amount of 20 wt% caustic solution needed to absorb the entire contents of an over filled one-ton cylinder. In addition, there is no foaming problem as has occurred with the use of high pressure or concentrated caustic solutions for scrubbing.

Scrubber Performance

This report will evaluate the performance of the Sentry 2000 Scrubber for the absorption of chlorine released as a liquid from a 1 ton cylinder into a ventilated room. Data collection and sample analyses were performed by Entropy Environmentalists, Inc. of Research Triangle Park, NC, specialists in air emission testing. The inlet and outlet gas flow rates were determined using EPA Methods 1-4. The chlorine concentration in the inlet gas stream was determined using EPA Method SW 846-0050 with a single sampling train. The chlorine concentration in the outlet gas stream (stack) was determined using EPA Method 26 with two parallel sampling trains.

The scrubber was located on a pad and connected to the flash room by an 18 inch diameter duct about 20 feet in length. The flash room was 10.5 ft wide by 15.5 ft long by 10 ft high giving a total volume of 1628 ft³. Liquid chlorine was released from a 1 ton cylinder located in an adjoining room and was discharged into a steel pan located 2 feet above the floor of the flash room. The flash room was maintained under a negative pressure of about 0.3 inches of water. Ventilation air entering the flash room flowed across the pan into the 18 inch duct.

The Sentry 2000 Scrubber was designed to handle 3000 ACFM of chlorine contaminated air. This scrubber contains four beds of plastic packing through which the gas stream passes horizontally in series. A 20 wt% sodium hydroxide solution is distributed onto the top of each packed bed in order to absorb the chlorine from the gas stream. This caustic solution is recirculated from the sump located beneath the packed section of the scrubber. The amount of caustic solution in the sump is sufficient to absorb the entire contents of 1.5 overfilled 1 ton cylinders. Tests were performed on August 11 & 12, 1993.

Scale-up Considerations

The performance of packed towers in absorption operations can be calculated by using one of two methods: the use of an overall mass transfer coefficient or the use of the transfer unit concept. A mass transfer coefficient represents the rate at which the solute is transferred from the gas phase to the liquid phase through one square foot of interfacial surface area with one atmosphere differential pressure driving force. At the interface there exists a gas film and a liquid film both of which offer resistance to solute transfer. The reciprocal of the overall mass transfer coefficient is equal to the sum of the reciprocal of the gas film mass transfer coefficient and the reciprocal of the liquid film mass transfer coefficient multiplied by a slope term. The slope term represents the ratio of the concentration of the solute in the gas phase that is in equilibrium with a given concentration of solute in the liquid phase to that concentration of solute in the liquid phase. Since there is a negligible equilibrium concentration of chlorine in a gas phase above a sodium hydroxide solution, the value of the slope term essentially is zero. Thus the overall mass transfer coefficient for this absorption is the same as the gas film mass transfer coefficient. A great many experiments have been conducted on gas film controlled absorption system which show that the mass transfer coefficient varies as the gas flow to an average power of 0.75. The gas flow is measured as vapor capacity factor, which is the square root of gas kinetic energy. The mass transfer coefficient also varies with the liquid irrigation rate. This variations a function of the liquid flow per square foot to a power between 0.24 and 0.32 for the various types of random packing in wide commercial use.

The driving force for mass transfer is the difference between the partial pressure of the solute in the gas phase and the vapor pressure of the solute above the liquid phase that are in contact. Since there is negligible vapor pressure of chlorine above the caustic solution, the driving force of this absorption is the partial pressure of chlorine in the gas phase.

The number of lb mol/h of chlorine to be absorbed can be calculated from the gas flow rate and the concentrations of chlorine in the inlet and outlet gas streams. A logarithmic average of the inlet and outlet chlorine concentrations in the gas phase expressed as partial pressures represents the overall driving force. For convenience in calculation, the experimentally determined mass transfer coefficients are expressed in lb mols/hour per cubic foot of packing per atmosphere of driving force. Thus, the interfacial area in square feet per cubic foot for a specific packing is combined with the mass transfer coefficient for that packing. The experimentally determined mass transfer coefficients are adjusted for the gas and liquid flows at the inlet and outlet of the scrubber. A logarithmic average of those two coefficients

represents the overall mass transfer coefficient expected. The quantity of packing required for a given absorption now can be determined.

A transfer unit is a mathematical integral which represents a change of solute concentration in the gas phase equal to the average driving force causing that change. For a system in which there is negligible concentration of solute in the gas phase in equilibrium with the liquid phase, the number of transfer units required for an absorption is given by the natural logarithm of the ratio of solute concentration in the inlet gas stream to the solute concentration in the outlet gas stream. A small correction factor is needed that increases the number of transfer units required when there is a high concentration of solute in the gas phase.

The overall height of a transfer unit is the sum of the height of a gas film transfer unit and the height of a liquid film transfer unit multiplied by a slope ratio term. For reasons outlined previously, the value of this slope ratio term essentially is zero. Thus the overall height of a transfer unit is the same as the height of a gas film transfer unit. The height of transfer until equals the molar gas flow rate per square foot divided by the mass transfer coefficient and the system pressure. A logarithmic average of the heights of a transfer unit based on the mass transfer coefficients at the gas inlet and the gas outlet is the overall height of a transfer unit predicted. The product of the number of transfer units, the overall height of a transfer unit, and the gas flow cross sectional area gives the quantity of packing needed.

Scrubber Tests

Test #1

On August 11th, 2012 lb of liquid chlorine were discharged from the cylinder at an average rate of 88.4 lb per minute. During the chlorine release, the concentration of chlorine in the inlet gas stream was 56,991 ppm by vol. The inlet gas flow was 3094 ACFM at 80.5°F and 29.6 inches of mercury barometric pressure. The caustic solution recycle rate was 394 gpm. The outlet gas temperature of 97°F was almost the same as the liquid temperature, which was expected since the mass flow of liquid was more than 16 times that of the inlet gas stream. The outlet gas flow corrected for temperature and water vapor content was calculated to be 3050 ACFM. The average measured chlorine concentration in the outlet gas stream was 3.63 ppm by vol. As the equilibrium partial pressure of chlorine above solutions containing a large excess of caustic essentially is zero, the driving force for mass transfer in the partial pressure of chlorine in the gas stream. Using the measured concentrations of chlorine in the inlet and outlet gas streams, the \ln mean mass transfer driving force was 0.005835 atm. The chlorine was absorbed during the release of chlorine from the cylinder at a rate of 26.538 lb mols per hour. Although the actual height of the scrubber beds is 48 inches, in order to allow for any effect of the gas baffles or the liquid distribution, the effective packed volume used in the calculations was the actual volume reduced to a packed height of 39 inches. These figures give an overall mass transfer coefficient of 25.443 lb mol per hour ft^3 atm. From the inlet and outlet chlorine concentrations in the gas streams, the number of transfer units developed in the scrubber can be calculated. The number of transfer units developed during the chlorine release was 9.691 corrected for the effect of the high concentration of chlorine in the inlet gas stream. The overall height of a transfer unit was 2.270 feet. Using the \ln mean average molar gas flow rate and this height of a transfer unit, the overall mass transfer coefficient for a gas film controlled absorption is 24.960 lb mol per hour ft^3 atm. Since these two values differ by only 1.9%, this absorption has been shown to be predominantly gas film controlled.

Test #2

On August 11th after all the chlorine had been discharged from the cylinder, a test was conducted while the residual liquid chlorine was evaporating from the steel pan located in the flash room. The concentration of chlorine in the inlet gas stream was 8100 ppm by vol. The inlet gas flow rate was 3113 ACFM at 80.5°F and 29.6 inches of mercury barometric pressure. The caustic solution recycle rate was 394 gpm and the outlet gas temperature was 97°F. The outlet gas flow rate corrected for temperature and water vapor content was calculated to be 3233 ACFM. The average measure chlorine concentration in the outlet gas stream was 0.36 ppm by vol. These concentrations gave

a \ln mean mass transfer driving force of 0.0007996 atm. The chlorine absorbed during vaporization of chlorine from the pan occurred at the rate of 3.7949 lb mols per hour. These figures give an overall mass transfer coefficient of 26.551 lb mols per hour ft^3 atm. The number of transfer units developed during the chlorine vaporization was 10.025. Thus the overall height of a transfer unit was 2.194 feet. Using the \ln mean average molar gas flow rate and this height of a transfer unit, the overall mass transfer coefficient during the chlorine vaporization is 26.666 lb mols per ft^3 atm. These two values of the overall mass transfer coefficient differ by less than 0.5%.

Test #3

On August 12th, 1744 lb of liquid chlorine were discharged from a cylinder at an average rate of 90.8 lb per minute. During the chlorine release, the concentrations of chlorine in the inlet gas stream was 53,420 ppm by vol. The inlet gas flow was 3024 ACFM at 85°F and 29.7 inches of mercury barometric pressure. The caustic solution recycle rate was 393 gpm and the outlet gas temperature was 95°F. The outlet gas flow corrected for temperature and water vapor content was calculated to be 2921 ACFM. The average measured chlorine concentration in the outlet gas stream was 5.08 ppm by vol. Using the measured concentrations of chlorine in the inlet and outlet gas streams, the \ln mean mass transfer driving force was 0.005726 atm. The chlorine was absorbed during the release of chlorine from the cylinder at a rate of 24.192 lb mols per hour. These figures give an overall mass transfer coefficient of 23.636 lb mol per hour ft^3 atm. The number of chlorine units developed during the chlorine release was 9.288 corrected for the effect of the high concentration of chlorine in the inlet gas stream. The overall height of a transfer unit was 2.369 feet. Using the \ln mean average molar gas flow rate and this height of a transfer unit, the overall mass transfer coefficient for a gas film controlled absorption is 23.093 lb mol per hour ft^3 atm. These two values of the overall mass transfer coefficient differ by only 2.3%.

Test #4

On August 12th after all the chlorine had been discharged from the cylinder, a test was conducted while the residual liquid chlorine was evaporating from the steel pan located in the flash room. The concentration of chlorine in the inlet gas stream was 7724 ppm by vol. The inlet gas flow rate was 3024 ACFM at 85°F and 29.7 inches of mercury barometric pressure. The caustic solution recycle rate was 393 gpm and the outlet gas temperature was 96°F. The outlet gas flow rate corrected for temperature and water vapor content was calculated to be 3078 ACFM. The average measured chlorine concentration in the outlet gas stream was 0.35

ppm by vol. These concentrations gave a \ln mean mass transfer driving force of 0.0007665 atm. The chlorine absorbed during the vaporization of chlorine from the pan occurred at the rate of 3.4980 lb mols per hour. These figures give an overall mass transfer coefficient of 25.531 lb mols per hour ft^3 atm. The number of transfer units developed during the chlorine vaporization was 10.006. Thus, the overall height of a transfer unit was 2.199 feet. Using the \ln mean average molar gas flow rate and this height of a transfer unit, the overall mass transfer coefficient during the chlorine vaporization is 25.510 lb mols per hour ft^3 atm. These two values of the overall mass transfer coefficient differ by less than 0.1%.

Discussion of Results

Since the mass transfer coefficients calculated from partial pressure driving forces and the mass transfer coefficients calculated from transfer units differ on average by only 1.1%, this absorption is predominantly gas film controlled. Chemical engineering theory indicates that the mass transfer coefficients for gas film controlled systems vary with both the gas and liquid flow rates. Adjusting the average of the experimentally determined mass transfer coefficients by means of theory to a gas inlet flow rate of 3000 ACFM and a liquid recycle rate of 400 gpm gives the following:

Mass transfer coefficient during the Aug. 11th chlorine discharge = 24.853 lb mols per hour ft³ atm.

Mass transfer coefficient during Aug. 11th residual evaporation = 25.948 lb mols per hour ft³ atm.

Mass transfer coefficient during the Aug. 12th chlorine discharge = 23.932 lb mols per hour ft³ atm.

Mass transfer coefficient during the Aug. 12th residual evaporation = 25.661 lb mols per hour ft³ atm.

The adjusted mass transfer coefficients during chlorine discharge from the cylinder agree within $\pm 1.9\%$ while the coefficients during residual chlorine evaporation agree within $\pm 0.56\%$. The chlorine release rate during both tests exceeded the 78.3 lb per minute rate equivalent to a discharging the contents of 2350 lbs of chlorine from the overfilled cylinder in 30 minutes. These adjusted mass transfer coefficients can be used with confidence to predict the performance of the Sentry 2000 Scrubber employing usual mass transfer design methods. Calculations can be made using either the partial pressure of chlorine as the driving force or using the transfer unit method. Further, these tests indicated that the mass transfer coefficients actually increase somewhat at lower concentrations of chlorine in the gas stream (as occurred during the residual chlorine evaporation from the pan). Therefore, very low concentrations of chlorine in the outlet gas stream can be achieved without loss of scrubbing efficiency.

Alternate Scrubber Operation

In order to demonstrate the effect of the gas flow rate on the performance of the Sentry 2000 Scrubber, assume an inlet gas rate of 1500 ACFM containing 55,200 ppm by vol. of chlorine. The gas enters at 83°F and leaves at 96°F. A 20 wt% caustic solution is recycled at 400 gpm. These conditions are similar to those of test #1 and #3 at a lower gas flow; therefore, the average mass transfer coefficient of 24.392 lb mol per hour ft³ atm. corrected for the lower gas flow rate will be 14.502 lb mol per hour ft³ atm for this liquid rate. Using both the mass transfer coefficient method and the transfer unit method, the chlorine concentration in the outlet gas stream can be determined. The outlet gas flow from the scrubber is calculated to be 1483 ACFM containing an average of 0.55 ppm by vol. of chlorine

Likewise, the liquid flow rate has an effect on the performance of the scrubber. Assume that for the above situation with 1500 ACFM of inlet gas that the liquid recycle rate is increased from 400 gpm to 500 gpm. Again both the mass transfer coefficient method and the transfer unit method will be used to calculate the concentration of chlorine in the outlet gas stream. The outlet gas flow from the scrubber remains at 1483 ACFM; however, the average chlorine concentration is reduced to 0.26 ppm by vol.

Since calculation methods for packed towers are well developed, it is possible to predict the performance of a fixed design under a variety of operating rates and concentrations. Conversely, for a specific flow rate and efficiency, the design of a suitable scrubber can be developed with confidence. Therefore, it is not necessary to perform tests on each size of scrubber to ascertain its performance.

Calculations

Test#1 Calculations

$3094 (29.6/29.92) (492/540.5) = 2786.25$ SCFM inlet gas flow

$2786.25/359 = 7.76114$ lb mol/min inlet gas flow

$0.056991 (7.76114) = 0.44232$ lb mol/min inlet Cl_2

$7.76114 - 0.44232 = 7.31882$ lb mol/min inlet humid air

$0.31 (7.76114) = 0.24060$ lb mol/min H_2O vapor inlet

$7.31882 - 0.24060 = 7.07822$ lb mol/min dry air inlet

$70.906(0.44232) + 18.015(0.24060) + 28.967(7.07822) = 240.732$ lb/min inlet gas flow

$240.732/3094 = 0.077806$ lb/ft³ density of inlet gas flow

Vapor pressure of H_2O above 20 wt% NaOH solution @ 97°F is 35.0 mm Hg

$35.0(100)/25.4(29.6) = 4.655$ mol% H_2O vapor outlet gas

$7.07822/(1 - 0.04655 - 3.63 \times 10^{-6}) = 7.42383$ lb mol/min outlet gas flow

$7.42383 (3.63 \times 10^{-6}) = 2.695 \times 10^{-5}$ lb mol/min outlet Cl_2

$7.42383 (0.04655) = 0.34558$ lb mol/min H_2O vapor outlet

$70.906(2.695 \times 10^{-5}) + 18.015(0.34558) + 28.967(7.07822) = 211.263$ lb/min outlet gas flow

$7.42383(359) = 2665.16$ SCFM outlet gas flow

$2665.16(29.92/29.6)(557/492) = 3049.88$ ACFM outlet gas flow

$211.263/3049.88 = 0.69269$ lb/ft³ density of outlet gas

$60(0.44232 - 2.695 \times 10^{-5}) = 26.5376$ lb mol/h Cl_2 absorbed

$29.6/29.92(0.056991 - 0) = 0.056382$ atm partial pressure Cl_2 in

$29.6/29.92(3.63 \times 10^{-6} - 0) = 3.591 \times 10^{-6}$ atm partial pressure Cl_2 out

$0.056382 - 3.591 \times 10^{-6} / \ln(0.056382/3.59 \times 10^{-6}) = 0.005835$ atm ln mean driving force

$39(30)/144 = 8.125$ ft. effective gas flow

$8.125 (22) = 178.75$ ft³ effective packing volume

$26.5376/178.75(0.005835) = 25.443$ lb mol/h*ft³*atm OVERALL MASS TRANSFER COEFFICIENT

$\ln(0.056991/3.63 \times 10^{-6}) + 0.5 \ln(1 - 3.63 \times 10^{-6} \times 1 - 0.056991) = 9.6908$ total transfer units developed

$22/9.6908 = 2.2702$ ft. overall height of a transfer unit

$60(7.76114) = 465.668$ lb mol/h inlet gas flow

$60(7.42383) = 445.430$ lb mol/h outlet gas flow

$465.668 - 445.430 / \ln(465.668/445.430) = 455.474$ lb mol/h ln mean gas flow

$29.6/29.92 = 0.98930$ atm system pressure

If absorption is gas film controlled

$455.474/2.2702(8.125)(0.98930) = 24.960$ lb mol/h*ft³*atm OVERALL MASS TRANSFER COEFFICIENT

$25.443 + 24.960/2 = 25.202$ lb mol/h*ft³*atm

Average overall mass transfer coefficient = 25.202

Test#2 Calculations

$$3113(29.6/29.92)(492/540.5) = 2803.36 \text{ SCFM inlet gas flow}$$

$$2803.36/359 = 7.80880 \text{ lb mol/min inlet gas flow}$$

$$0.008100(7.80880) = 0.063521 \text{ lb mol/min inlet Cl}_2$$

$$0.031(7.80880) = 0.24207 \text{ lb mol/min inlet H}_2\text{O vapor}$$

$$7.80880 - 0.24207 - 0.063251 = 7.50348 \text{ lb mol/min dry air inlet}$$

$$7.50348/(1 - 0.04655 - 3.6 \times 10^{-7}) = 7.86982 \text{ lb mol/min outlet gas flow}$$

$$3.6 \times 10^{-7}(7.86982) = 2.833 \times 10^{-6} \text{ lb mol/min outlet Cl}_2$$

$$60(0.063251 - 2.833 \times 10^{-6}) = 3.7949 \text{ lb mol/hr Cl}_2 \text{ absorbed}$$

$$29.6/29.92(0.008100 - 0) = 0.0080314 \text{ atm partial pressure Cl}_2 \text{ in}$$

$$29.6/29.92(3.6 \times 10^{-7}) = 3.562 \times 10^{-7} \text{ atm partial pressure Cl}_2 \text{ out}$$

$$0.0080314 - 3.562 \times 10^{-7}/\ln(0.0080314/3.562 \times 10^{-7}) = 7.996 \times 10^{-4} \text{ atm In mean driving force}$$

$$3.7949/178.75(7996 \times 10^{-4}) = 26.551 \text{ lb mol/h*ft}^3\text{*atm OVERALL MASS TRANSFER COEFFICIENT}$$

$$7.86985(359) = 2825.27 \text{ SCFM outlet gas flow}$$

$$2825.27(29.92/29.6)(557/492) = 3233.11 \text{ ACFM outlet gas flow}$$

$$\ln(0.00810/3.6 \times 10^{-7}) + 0.5\ln(1 - 3.6 \times 10^{-7}/1 - 0.008100) = 10.0253 \text{ total transfer units developed}$$

$$22/10.0253 = 2.1944 \text{ ft. overall height of a transfer unit}$$

$$60(7.80880) = 468.528 \text{ lb mol/h inlet gas flow}$$

$$60(7.86982) = 472.189 \text{ lb mol/h outlet gas flow}$$

$$468.528-472.189/\ln(468.528/472.189) = 470.356 \text{ lb mol/h In mean gas flow}$$

$$470.356/2.1944(8.125)(0.98930) = 26.666 \text{ lb mol/h*ft}^3\text{* atm OVERALL MASS TRANSFER COEFFICIENT}$$

$$26.551 + 26.666/2 = 26.608 \text{ lb mol/h*ft}^3\text{*atm}$$

$$\text{Average overall mass transfer coefficient} = 26.608$$

Test #3 Calculations

$$3024(29.7/29.92)(492/545) = 2709.85 \text{ SCFM inlet gas flow}$$

$$2709.85/359 = 7.54833 \text{ lb mol/min inlet gas flow}$$

$$0.053420(7.54833) = 0.40323 \text{ lb mol/min inlet Cl}_2$$

$$7.54833 - 0.40323 = 7.14510 \text{ lb mol/min inlet humid air}$$

$$0.040(7.54833) = 0.30193 \text{ lb mol/min H}_2\text{O vapor inlet}$$

$$7.14510 - 0.30193 = 6.84317 \text{ lb mol/min dry air inlet}$$

$$70.906(0.40323) + 18.015(0.30193) + 28.967(6.84317) = 232.257 \text{ lb/min inlet gas flow}$$

$$232.257/3024 = 0.076805 \text{ lb/ft}^3 \text{ density of inlet gas}$$

$$\text{Vapor pressure of H}_2\text{O above 20 wt\% NaOH solution @ 95}^\circ\text{F is 33.4 mm Hg}$$

$$33.4(100) = 4.427 \text{ mol\% H}_2\text{O vapor outlet gas}$$

$$6.84317/(1 - 0.04427 - 5.08 \times 10^{-6}) = 7.16019 \text{ lb mol/min outlet gas flow}$$

$$7.16019(5.08 \times 10^{-6}) = 3.637 \times 10^{-5} \text{ lb mol/min outlet Cl}_2$$

$$7.16019(0.04427) = 0.31695 \text{ lb mol/min H}_2\text{O vapor outlet}$$

$$70.906(3.637 \times 10^{-5}) + 18.015(0.31695) + 28.967(6.84317) = 203.939 \text{ lb/min outlet gas flow}$$

$$7.16019(359) = 2570.51 \text{ SCFM outlet gas flow}$$

$$2570.51(29.92/29.7)(555/492) = 2921.14 \text{ ACFM outlet gas flow}$$

$$203.939/2921.14 = 0.69815 \text{ lb/ft}^3 \text{ density of outlet gas}$$

$$60(0.40323 - 3.637 \times 10^{-5}) = 24.1917 \text{ lb mol/h Cl}_2 \text{ absorbed}$$

$$29.7/29.92(0.053420 - 0) = 0.053027 \text{ atm partial pressure Cl}_2 \text{ in}$$

$$29.7/29.92(5.08 \times 10^{-5}) = 5.043 \times 10^{-6} \text{ atm partial pressure Cl}_2 \text{ out}$$

$$0.053027 - 5.043 \times 10^{-6} / \ln(0.053027/5.043 \times 10^{-6}) = 0.005726 \text{ atm ln mean driving force}$$

$$24.1917/178.75(0.005726) = 23.636 \text{ lb mol/h*ft}^3\text{*atm OVERALL MASS TRANSFER COEFFICIENT}$$

$$\ln(0.053420/5.08 \times 10^{-6}) + 0.5\ln(1 - 5.08 \times 10^{-6}/1 - 0.053420) = 9.2881 \text{ total transfer units developed}$$

$$22/9.2881 = 2.3686 \text{ ft overall height of a transfer unit}$$

$$60(7.54833) = 452.900 \text{ lb mol/h inlet gas flow}$$

$$60(7.16019) = 429.611 \text{ lb mol/h outlet gas flow}$$

$$452.900 - 429.611 / \ln(452.900/429.611) = 441.153 \text{ lb mol/h ln mean gas flow}$$

$$29.7/29.92 = 0.99265 \text{ atm system pressure}$$

$$1.153/2.3686(8.125)(0.99265) = 23.093 \text{ lb mol/h*ft}^3\text{*atm OVERALL MASS TRANSFER COEFFICIENT}$$

$$23.636 = 23.093/2 = 23.365 \text{ lb mol/h*ft}^3\text{* atm}$$

$$\text{Average overall mass transfer coefficient} = 23.365$$

Test #4 Calculations

$$3024(29.7/29.92)(492/545) = 2709.85 \text{ SCFM inlet gas flow}$$

$$2709.85/359 = 7.54833 \text{ lb mol/min inlet gas flow}$$

$$0.007724(7.54833) = 0.058303 \text{ lb mol/min inlet Cl}_2$$

$$0.040(7.54833) = 0.30193 \text{ lb mol/min inlet H}_2\text{O vapor}$$

$$7.54833 - 0.30193 - 0.058303 = 7.18810 \text{ lb mol/min dry air inlet}$$

Vapor pressure of H₂O above 20 wt% NaOH solution @ 96°F is 34.3 mm Hg

$$34.3(100)/25.4(29.7) = 4.547 \text{ mol\% H}_2\text{O vapor outlet gas}$$

$$7.18810/(1 - 0.04547 - 3.5 \times 10^{-7}) = 7.53051 \text{ lb mol/min outlet gas flow}$$

$$7.53051(3.5 \times 10^{-7}) - 2.636 \times 10^{-6} \text{ lb mol/min outlet Cl}_2$$

$$60(0.058303 - 2.636 \times 10^{-6}) = 3.4980 \text{ lb mol/h Cl}_2 \text{ absorbed}$$

$$29.7/29.92(0.007724 - 0) - 0.0076672 \text{ atm partial pressure Cl}_2 \text{ in}$$

$$29.7/29.92(3.5 \times 10^{-7}) = 3.474 \times 10^{-7} \text{ atm partial pressure Cl}_2 \text{ out}$$

$$0.0076672 - 3.474 \times 10^{-7} / \ln(0.0076672/3.474 \times 10^{-7}) = 7.665 \times 10^{-4} \text{ atm ln mean driving force}$$

$$3.4980/178.75(7.665 \times 10^{-4}) = 25.531 \text{ lb mol/h*ft}^3\text{*atm OVERALL MASS TRANSFER COEFFICIENT}$$

$$7.53051(359) = 2703.45 \text{ SCFM outlet gas flow}$$

$$2703.45(29.92/29.7)(556/492) = 3077.75 \text{ ACFM outlet gas flow}$$

$$\ln(0.007724/3.5 \times 10^{-7}) + 0.5 \ln(1 - 3.5 \times 10^{-7}/1 - 0.007724) = 10.0058 \text{ total transfer units developed}$$

$$22/10.0058 = 2.1987 \text{ ft overall height of a transfer unit}$$

$$60(7.54833) = 452.900 \text{ lb mol/h inlet gas flow}$$

$$60(7.53051) = 451.831 \text{ lb mol/outlet gas flow}$$

$$452.900 - 451.831 / \ln(452.900/451.831) = 452.365 \text{ lb mol/h ln mean gas flow}$$

$$452.365/2.1987(8.125)(0.99265) = 25.510 \text{ lb mol/h*ft}^3\text{*atm OVERALL MASS TRANSFER COEFFICIENT}$$

$$25.531 + 25.510/2 = 25.520 \text{ lb mol/h*ft}^3\text{*atm}$$

$$\text{Average overall mass transfer coefficient} = 25.520$$