

Full Length Research Paper

Toxic acid gas absorber design considerations for air pollution control in process industries

S. V. Manyele

Department of Chemical and Process Engineering, College of Engineering and Technology, University of Dar es Salaam, P.O. Box 35131, Dar es Salaam, Tanzania. E-mail: smanyele@cpe.udsm.ac.tz.

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This paper analyses the design parameters for an absorber used for removal of toxic acid gas (in particular sulfur dioxide) from a process gas stream for environmental health protection purposes. Starting from the equilibrium data, Henry's law constant was determined from the slope of the y-x diagram. Based on mass balances across the absorber, the minimum liquid-to-gas ratio was determined from which the minimum liquid flow rate and the actual operating conditions were established. Using a generalized flooding and pressure drop correlation, and the mass flow rates of liquid and gas, the mass flow rate of the gas per unit cross sectional area of the tower was determined. The operating point (ranging from 50 to 75% of flooding velocity) was used to determine the required cross-sectional area and diameter of the absorption tower. The operating liquid flow rate was observed to depend strongly on the inlet gas flow rate, solute concentration in the inlet liquid, and solute removal efficiency. The solute removal efficiency was varied from 80 to 99% at a fixed inlet toxic gas concentration of 3%. The tower diameter was observed to depend strongly on: the inlet total gas flow rate, percent of the flooding velocity selected, packing factor, size of packing, and on the type of material used (at fixed size of packing). The tower height, which was observed to depend strongly on toxic gas concentration in the inlet gas, and on the required toxic pollutant removal efficiency, was, however, independent of gas and liquid flow rates.

Key words: Gas absorption; packed tower; solubility data; design criteria; removal efficiency; minimum liquid flow rate; operating line equation, packed tower size.

INTRODUCTION

Absorption is a process that refers to the transfer of a toxic gaseous pollutant from a gas phase to a liquid phase. More specifically, in air pollution control, absorption involves the removal of objectionable toxic gaseous pollutants from a process stream by dissolving them in a liquid. The absorption process can be categorized as physical or chemical. Physical absorption occurs when the absorbed compound dissolves in the liquid, while chemical absorption occurs when the absorbed compound(s) and the liquid (or reagents in the liquid) react (Gumnitsky and Dereyko, 2007).

Toxic gas absorbers are most often used to remove soluble inorganic contaminants from an air stream. The design of an absorber used to reduce toxic gaseous pollutants from process exhaust streams involves many factors including the toxic pollutant collection efficiency,

toxic pollutant solubility in the absorbing liquid, liquid-to-gas ratio (Huang, 2005); exhaust flow rate, pressure drop, and many construction details of the absorbers such as packing, plates, liquid distributors, entrainment separators, and corrosion-resistant materials.

In this study, SO₂ removal is studied extensively (Nolan, 2000; Rubin et al., 2004). Flue gas desulfurization (FGD) is the current state-of-the art technology used for removing sulfur dioxide (SO₂) from the exhaust flue gases in power plants that burn coal or oil to produce steam for the steam turbines that drive electricity generators (Witte and Kind, 1986). Sulfur dioxide is responsible for acid rain formation. Tall flue gas stacks disperse the emissions by diluting the pollutants in ambient air and transporting them to other regions. As of June 1973, there were 42 FGD units, ranging in size

from 5 MW to 250 MW, in operation: 36 in Japan and 6 in the United States. As of about 1999-2000, FGD units were being used in 27 countries and there were 678 FGD units operating on a total power plant capacity of about 229 GW. About 45% of that FGD capacity was in the U.S., 24% in Germany, 11% in Japan and 20% in various other countries. Approximately 79% of the units, representing about 199 GW of capacity were using lime or limestone wet scrubbing. About 18% (or 25 GW) utilized spray-dry scrubbers or sorbent injection systems (Nolan, 2000; Rubin et al., 2004).

The theoretical relationships for toxic gas absorption have been well defined over the many years that toxic gas absorption has been implemented in process industries; however, they can be very complex and are dependent on the mechanical design of the absorber. As with particulate scrubbers, empirical relationships and general rules of thumb are often used to evaluate absorber designs and there is no one easy set of equations to evaluate the design of all absorbers. All wet scrubbing systems are able to collect both particulate and toxic gaseous pollutants emitted from process exhaust streams (Shabunya et al., 2003). However, spray towers, plate towers, packed towers, and moving-bed scrubbers are most often used for toxic gaseous pollutant removal. This paper focuses on equations used to estimate liquid flow rate, the diameter and the height of a packed tower required to achieve specified toxic pollutant removal efficiency.

The principal design criteria are the exhaust flow rate to the absorber, measured in units of m^3/min , and the toxic gaseous pollutant concentration, measured in units of parts per million (ppm), mole fraction or percent. The exhaust volume and toxic pollutant concentration are set by the process exhaust conditions, like emission rate. The design plans should consider the factors such as exhaust gas characteristics (average and maximum flow rates to the absorber), and solubility of the toxic pollutant to be removed should be measured or accurately estimated. Another important parameter is the liquid flow (the type of scrubbing liquid and the rate at which the liquid is supplied to the absorber). If the liquid is to be recirculated, the pH and amount of suspended solids (if any) should be monitored to ensure continuous reliability of the absorbing system. Liquids commonly used as solvents include water, mineral oils, nonvolatile hydrocarbon oils, Fe/EDTA (Horikawa et al., 2004), aqueous solutions (Huttenhuis et al., 2007; Mukherjee et al., 2007), MEA (methyl-ethanolamine), MDEA (methyl-ethanolamine) (Kaewschan et al., 2001).

The pressure drop (gas-side) and pH at which the absorber will operate should be considered (Chatterjee and Joshi, 2008) and monitored during operation so that the acidity or alkalinity of the absorbing liquor can be properly adjusted. Mists and liquid droplets that become entrained in the "scrubbed" exhaust stream should be removed before exiting the stack. Some type of

entrainment separator, or mist eliminator, should be included in the design. Emission standards in terms of final toxic pollutant concentration, collection efficiency (in percent) required to meet the air pollution regulations should be observed. The collection efficiency can be high (90 to 99%) if the absorber is properly designed (Horikawa et al., 2004; Huang, 2005; Gumnitsky and Dereyko, 2007).

Absorbers remove toxic gaseous pollutants by dissolving them into a liquid called the absorbent (Kaewschan et al., 2001). In designing absorbers, optimum absorption efficiency can be achieved by doing the following: providing a large interfacial contact area; providing for good mixing between the gas and liquid phases; allowing sufficient residence, or contact, time between the phases; and choosing a liquid in which the toxic gaseous pollutant is very soluble.

Absorption is a mass-transfer operation. In absorption, mass transfer of the toxic gaseous pollutant into the liquid occurs as a result of a concentration difference (of the toxic pollutant) between the liquid and gas phases. Absorption continues as long as a concentration difference exists where the toxic gaseous pollutant and liquid are not in equilibrium with each other. The concentration difference depends on the solubility of the toxic gaseous pollutant in the liquid.

Solubility is an important factor which determines the amount of a toxic pollutant that can be absorbed (Mukherjee et al., 2007). Solubility is a function of both the temperature and, to a lesser extent, the pressure of the system. Solubility data are obtained at equilibrium conditions, which involve putting measured amounts of a gas and a liquid into a closed vessel and allowing the two to interact for a period of time until equilibrium is reached.

Equilibrium conditions are important in operating an absorption tower. If equilibrium were to be reached in the actual operation of an absorption tower, the collection efficiency would fall to zero since no net mass transfer could occur. Hence, absorption process is normally carried out away from equilibrium conditions, actually, above the equilibrium curve, as described later.

The effectiveness of an absorption system in toxic gas removal depends on the solubility of the gaseous contaminant. For very soluble gases, almost any type of absorber will give adequate removal. However, for most gases, only absorbers that provide a high degree of turbulent contact and a long residence time are capable of achieving high absorption efficiencies.

The two most common high-efficiency absorbers are plate and packed towers. Both of these devices are used extensively to control toxic gaseous pollutants. Absorber design calculations presented in this will focus on packed towers. Numerous procedures are used to design an absorption system. These procedures range in difficulty and cost from short-cut "rules of thumb" equations to in-depth design procedures based on pilot plant data. Procedures presented here will be based on

the short-cut "rules of thumb." The approaches discussed in this paper are for single component systems (only one toxic gaseous pollutant).

When an absorption system is designed, certain parameters are set by either operating conditions (like gas flow rate from the exhaust) or regulations (like allowable concentration of a pollutant in the exit gas from absorber). The gas stream to be treated is usually the exhaust from a process in the plant. Therefore, the volume, temperature, and composition of the gas stream entering the absorber are known parameters. The outlet composition of the contaminant is set by the emission standard which must be met. The temperature and inlet composition of the absorbing liquid are also usually known. The main unknowns in designing the absorption system are the following: the flow rate of liquid required; the diameter of the vessel needed to accommodate the gas and liquid flow; and the height of absorber required to achieve the needed removal (Blauwhoff et al., 1985; Rahimpour and Kashkooli, 2004; Bekassy-Molnar et al., 2005).

Modeling of absorber design

Equilibrium conditions and mass transfer theories

The absorber design begins with application of Henry's law in expressing equilibrium solubility of gas-liquid systems (Kaewschan et al., 2001; Huttenhuis et al., 2007; Mukherjee et al., 2007; Pröll et al., 2007; Chatterjee and Joshi, 2008). Henry's law is expressed as:

$$p = Hx \quad (1)$$

Where: p = partial pressure of solute at equilibrium (Pa); x = mole fraction of solute in the liquid; and H = Henry's law constant (Pa/mole fraction).

In Equation (1), H has the units of pressure per concentration. Henry's law can be written in a more useful form by dividing both sides of Equation (1) by the total pressure, P_T , of the system. The left side of the equation becomes the partial pressure divided by the total pressure, which equals the mole fraction of the solute in the gas phase, y , that is,

$$y = H'x \quad (2)$$

Where: y = mole fraction of toxic gas in the gas which is at equilibrium with the liquid; H' = Henry's law constant (mole fraction in vapor per mole fraction in liquid); x =

mole fraction of the solute in the liquid at equilibrium.

Henry's law can be used to predict solubility only when the equilibrium line is straight. Equilibrium lines are usually straight when the solute concentrations are very dilute, a case observed in air pollution control applications. Another restriction on using Henry's law is that it does not hold true for gases that react or dissociate upon dissolution. If this happens, the toxic gas no longer exists as a simple molecule. For example, scrubbing SO_2 (Witte and Kind, 1986), HF or HCl gases with water causes both compounds to dissociate in solution. In these cases, the equilibrium lines are curved rather than straight. Data on systems that exhibit curved equilibrium lines must be obtained from experiments. In this paper, SO_2 removal from a gaseous stream will be used as a case study (acid desulphurization) (Witte and Kind, 1986; Nolan, 2000; Rubin et al., 2004).

Given the concentration of a toxic gaseous pollutant in a solvent (P_{SO_2} , in this case) and the partial pressure of the solute, the mole fraction of the solute in the gas phase, y , can be calculated by dividing the partial pressure of the solute by the total pressure of the system, as shown in Equation (3):

$$y = \frac{P_{\text{SO}_2}}{P_T} \quad (3)$$

The mole fraction of the solute in the liquid phase, x , is then calculated by dividing the moles of the solute dissolved into the solution by the total moles of liquid. Plotting the mole fraction of the solute in the gas phase, (y), against the mole fraction of the solute in the solvent, (x) gives a straight line (called operating line equation) signifying that Henry's law applies. The slope of the line, ($\Delta y/\Delta x$), is the Henry's law constant (H').

If H' is very small (which means the toxic gas is very soluble in the liquid), then absorption is said to be gas-film controlled, that is, the major resistance to mass transfer is in the gas phase. Conversely, if a toxic gas has limited solubility, H' is large, and the mass-transfer rate is liquid-film controlled and depends on the solute's dispersion rate in the liquid phase. Most systems in the air pollution control field are gas-phase controlled since the liquid is chosen so that the solute will have a high degree of solubility.

The above analysis is based on mass transfer models (Diab and Maddox, 1982); that is, the film theory (Whitman, 1923); penetration theory (Higbie, 1935); surface renewal theory (Danckwerts, 1951); and the film-penetration theory (Toor and Marchello, 1958). The two-film model, for instance, starts by assuming that the gas and liquid phases are in turbulent contact with each other, separated by an interface area where they meet. This assumption may be correct, but no mathematical

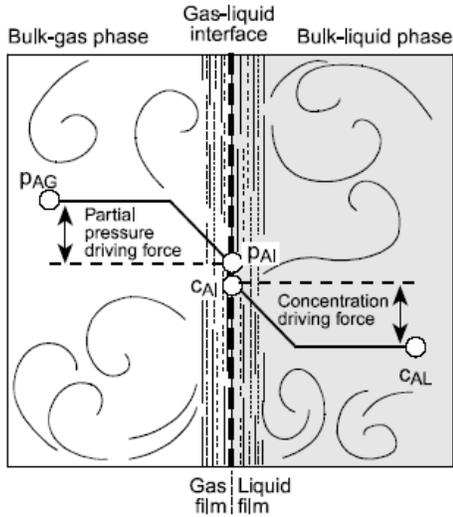


Figure 1. Visualization of two-film theory.

expressions adequately describe the transport of a molecule through both phases in turbulent motion. Therefore, the model proposes that a mass-transfer zone exists to include a small portion (film) of the gas and liquid phases on either side of the interface. The mass-transfer zone is comprised of two films, a gas film and a liquid film on their respective sides of the interface. These films are assumed to flow in a laminar, or streamline, motion (Peytavy et al., 1990). In laminar flow, molecular motion occurs by diffusion, and can be categorized by mathematical expressions. This concept of the two-film theory is illustrated in Figure 1. However, laminar flow is difficult to attain in industrial absorption process. The theory is useful for creating understanding of the theoretical principles.

Determination of liquid flow rate using mass balance

In designing an absorption control system, the first task is to determine the flow rates and composition of each stream entering the system. From the law of conservation of mass, the material entering a process must either accumulate or exit. In other words, "what comes in must go out." A material balance helps determine flow rates and compositions of individual streams not only across the absorption process but also in all process setups.

Engineering design work is usually done on a solute-free basis (X, Y) which means we ignore the amount of toxic pollutant being transferred from the gas to the liquid. This makes the material balance calculations easier because we do not have to continually account for the change in mass of the flue gas as it is losing a toxic pollutant, or of the liquid as it is gaining the toxic pollutant. The solute-free basis is defined in Equations (4) and (5)

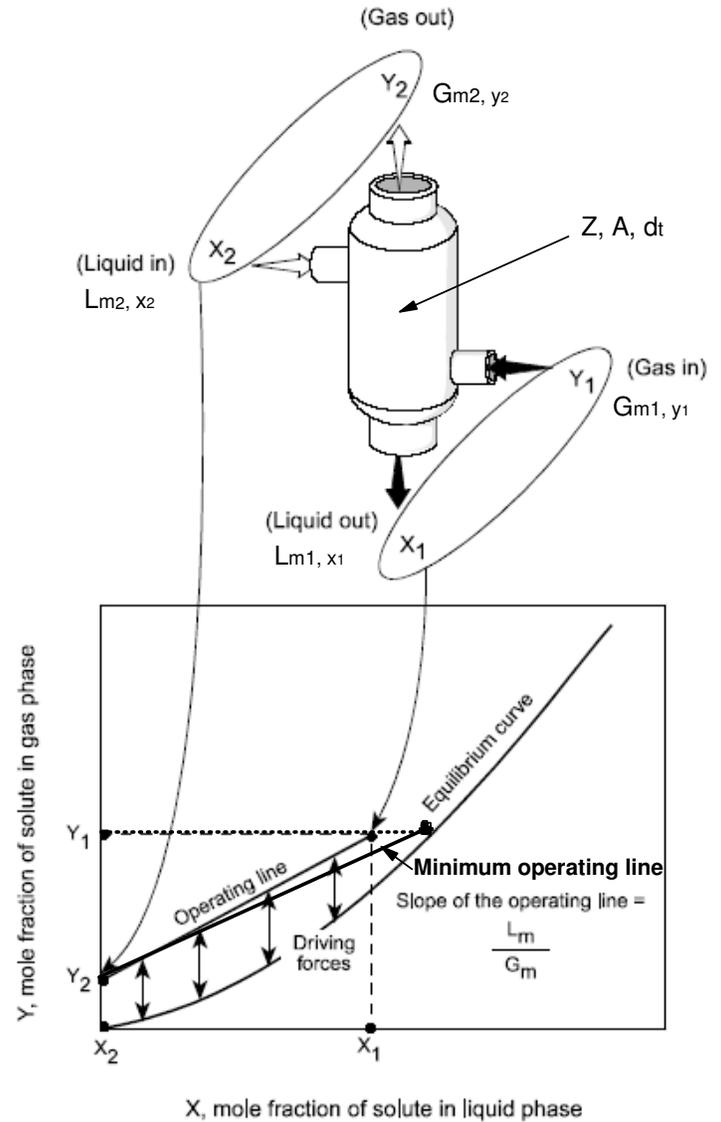


Figure 2. Material balance for countercurrent flow absorber and the corresponding operating line diagram.

$$Y = \frac{y}{1 - y} \tag{4}$$

$$X = \frac{x}{1 - x} \tag{5}$$

Figure 2 illustrates the material balance for a typical countercurrent-flow absorber. The solute is the "key component" in the material balance across an absorber. A material balance for the contaminant to be removed is obtained as expressed in Equation (6):

$$\frac{L_m}{G_m} = \frac{Y_1 - Y_2}{X_1 - X_2} \quad (6)$$

Equation (6) gives a straight line. When this line is plotted on an equilibrium diagram, it is referred to as an operating line. Using this equation, it is possible to estimate the composition of the gas leaving the absorber by assuming that equilibrium has been reached (Coulson and Richardson, 1991; Horikawa et al., 2004).

This line defines operating conditions within the absorber: what is going in and what is coming out. An equilibrium diagram with a typical operating line plotted on it is shown in Figure 2.

The slope of the operating line is the liquid mass flow rate divided by the gas mass flow rate, which is the liquid-to-gas ratio, or L_m/G_m . The liquid-to-gas ratio is used extensively when describing or comparing different absorption systems. In the design of most absorption columns, the quantity of exhaust gas to be treated (G_m) and the inlet solute concentration (Y_1) are set by process conditions. Minimum acceptable standards specify the outlet toxic pollutant concentration (Y_2) as shown in Figure 2. The composition of the liquid flowing into the absorber (X_2) is also generally known or can be assumed to be zero if it is not recycled. It should be noted that the bottom part of the absorber is denoted as (1) (X_1, Y_1) and the top part as (2) (X_2, Y_2). During absorption process, X increases from X_2 to X_1 while Y from Y_1 to Y_2 . By plotting this data on an equilibrium diagram, the minimum liquid flow rate required to achieve the required outlet toxic pollutant concentration (Y_2) can be determined, as shown in Figure 2.

Determining the minimum liquid flow rate, $(L_m/G_m)_{min}$, is important since absorber operation is usually specified as some factor of it. Generally, liquid flow rates are specified at 25 to 100% greater than the required minimum. Typical absorber operation would be 50% greater than the minimum liquid flow rate (i.e., 1.5 times the minimum liquid-to-gas ratio). Setting the liquid flow rate in this way assumes that the gas flow rate set by the process does not change appreciably. Line AC in Figure 4 is drawn at a slope of 1.5 times the minimum L_m/G_m . The actual operating line describes absorber operating conditions and is above the minimum operating line and the equilibrium curve.

Sizing a packed tower

Packed tower diameter

The main parameter affecting the size of a packed column is the gas velocity at which liquid droplets become entrained in the exiting gas stream. Consider a packed column operating at specified gas and liquid flow

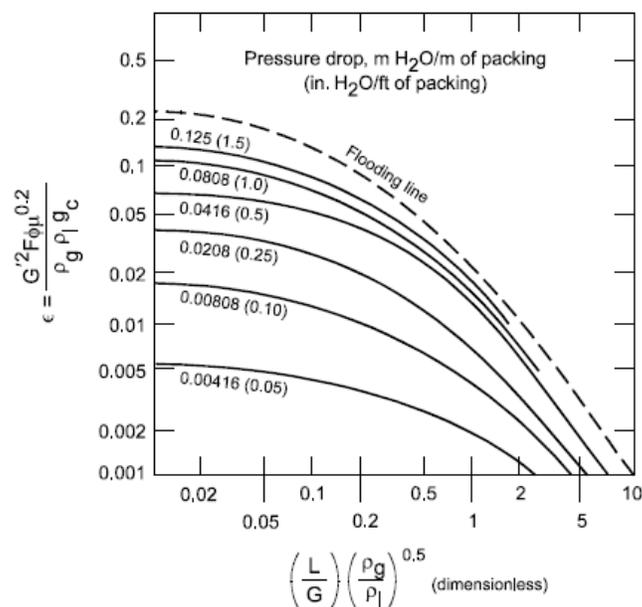


Figure 3. Generalized flooding and pressure drop correlation.

rates. By decreasing the diameter of the column, the gas flow rate (m/s or ft/sec) through the column will increase. If the gas flow rate through the column is gradually increased (by using smaller and smaller diameter columns), a point will be reached where the liquid flowing down over the packing begins to be held in the void spaces between the packing. This gas-to-liquid ratio is termed the loading point. The pressure drop of the column begins to increase and the degree of mixing between the phases decreases. A further increase in gas velocity will cause the liquid to completely fill the void spaces in the packing. The liquid forms a layer over the top of the packing and no more liquid can flow down through the tower. The pressure drop increases substantially, and mixing between the phases is minimal. This condition is referred to as flooding, and the gas velocity at which it occurs is the flooding velocity. Using an extremely large-diameter tower would eliminate this problem. However, as the diameter increases, the cost of the tower increases.

Normal practice is to size a packed column diameter to operate below flooding velocity, that is, at a certain percent of the flooding velocity. A typical operating range for the gas velocity through the columns is 50 to 75% of the flooding velocity. It is assumed that, by operating in this range, the gas velocity will also be below the loading point.

A common and relatively simple procedure for estimating flooding velocity (thus, setting a minimum column diameter) is to use a generalized flooding and pressure drop correlation. One version of the flooding and pressure drop relationship for a packed tower is in the Sherwood correlation, shown in Figure 3 (Calvert et al., 1972; Coulson and Richardson, 1991).

Figure 3 was developed from experimental data, so that units must be used as presented since the relationships are based on empirical data. The "X" axis (or abscissa) is a function of the physical properties of the gas and liquid streams, expressed as per equation (7):

$$\text{Abscissa} = \left(\frac{L}{G} \right) \left(\frac{\rho_g}{\rho_l} \right)^{0.5} \quad (7)$$

Where: L and G = mass flow rates (any consistent set of units may be used as long as the term is dimensionless); ρ_g = density of the gas stream; ρ_l = density of the absorbing liquid.

The "Y" axis (ordinate) is also a function of the gas and liquid properties as well as the packing material utilized. The graph is used to predict what conditions will cause flooding to occur. Since flooding is an unacceptable operating condition, this sets a minimum tower diameter for a given set of gas/liquid conditions. Knowing minimum unacceptable diameter, a larger, operating diameter can be specified. Knowing the value of the abscissa, the value of ordinate is read from the graph based on flooding conditions. The value of the flooding gas velocity is then determined from the Equation 8:

$$G' = \left[\frac{(\epsilon)(\rho_g)(\rho_l)(g_c)}{F\phi\mu_l^{0.2}} \right]^{0.5} \quad (8)$$

Where: G' = mass flow rate of gas per unit cross-sectional area of column, $\text{kg/m}^2 \text{ s}$; ρ_g = density of the gas stream (kg/m^3); ρ_l = density of the absorbing liquid, (kg/m^3); g_c = gravitational constant, 9.82 m/s^2 ; F = packing factor (Bhatia, 1977); ϕ = ratio of specific gravity of the scrubbing liquid to that of water; and μ_l = viscosity the of liquid.

The value of G' at operating conditions is determined by using equation 9:

$$G'_{\text{operating}} = (f)(G'_{\text{flooding}}) \quad (9)$$

Where: f = the percent of flooding velocity, usually 50 to 75%. The cross-sectional area and the diameter of the tower are determined from the equations 10 and 11:

$$A = \frac{G}{G'_{\text{operating}}} \quad (10)$$

$$d_t = \left(\frac{4A}{\pi} \right)^{0.5} \quad (11)$$

Packed tower height

The height of a packed column refers to the depth of packing material needed to accomplish the required removal efficiency. The more difficult the separation, the larger the packing height required. For example, a much larger packing height would be required to remove SO_2 than to remove chlorine from exhaust stream using water as the absorbent because chlorine is more soluble in water than SO_2 (Nolan, 2000; Rubin et al., 2004). Determining the proper height of packing is important since it affects both the rate and efficiency of absorption.

A number of theoretical equations are used to predict the required packing height. These equations are based on diffusion principles (Peytavy et al., 1990). The general form of the design equation for a gas-phase controlled resistance is given in Equation (12):

$$Z = \frac{G'}{K_{OG}aP} \int_{Y_2}^{Y_1} \frac{dY}{(1-Y)(Y-Y^*)} \quad (12)$$

Where: Z = height of packing (m); G' = mass flow rate of gas per unit cross-sectional area of column ($\text{g/m}^2\text{s}$); K_{OG} = overall mass-transfer coefficient based on the gas phase ($\text{g-mol/h.m}^2.\text{Pa}$); a = interfacial contact area (m^2); P = pressure of the system (kPa); and Y^* = toxic pollutant concentration in gas at equilibrium.

In analyzing Equation (12), the term $(G'/K_{OG}.a.P)$ has the dimension of meters and is defined as the height of a transfer unit (HTU). The term inside the integral is dimensionless and represents the number of transfer units (NTU) needed to make up the total packing height. Using the concept of transfer units, Equation (12) can be simplified to:

$$Z = \text{HTU} \times \text{NTU} \quad Z = N_{OG}H_{OG} = N_{OL}H_{OL} \quad (13)$$

Where : N_{OG} = number of transfer units based on an

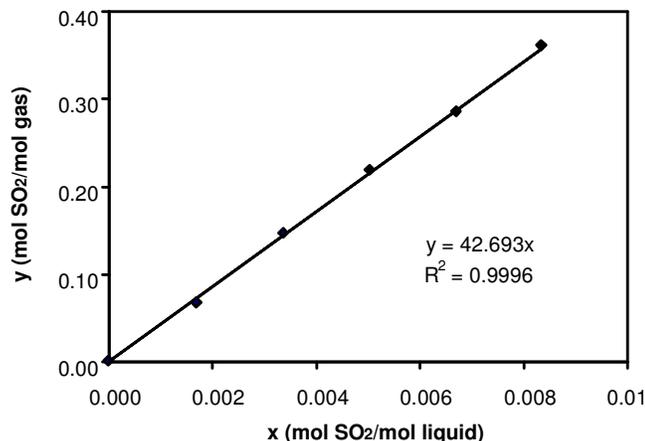


Figure 4. Equilibrium (y-x) diagram for SO₂-water system at 30°C.

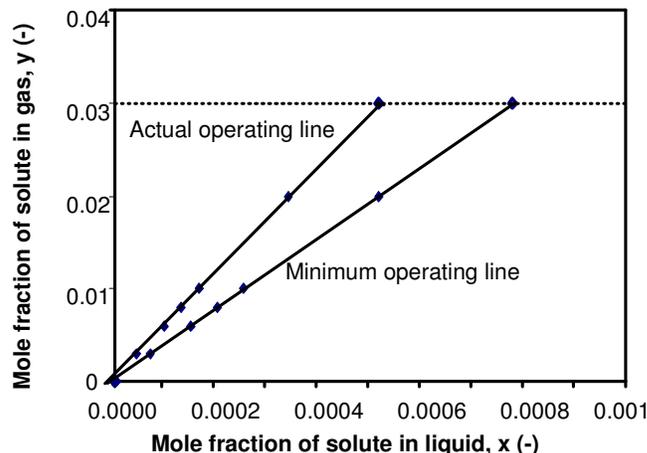


Figure 5. Actual and minimum operating lines on the y-x diagram.

overall gas-film coefficient, K_{OG} ; N_{OL} = number of transfer units based on an overall liquid film coefficient, K_{OL} ; H_{OG} = height of a transfer unit based on an overall gas-film coefficient, m ; H_{OL} = height of a transfer unit based on an overall liquid-film coefficient, m .

The number of transfer units, NTU (Coulson and Richardson, 1991), can be obtained experimentally or calculated from a variety of methods. For the case where the solute concentration is very low and the equilibrium line is straight, Equation (13) can be used to determine the number of transfer units (N_{OG}) based on the gas-phase resistance (Peytavy et al., 1990). Equation (13) can be derived from the integral portion of Equation (12), leading to:

$$N_{OG} = \frac{\ln \left[\left(\frac{Y_1 - mX_2}{Y_2 - mX_2} \right) \left(1 - \frac{mG_m}{L_m} \right) + \frac{mG_m}{L_m} \right]}{1 - \frac{mG_m}{L_m}} \quad (14)$$

METHODOLOGY

The main purpose was to study the effect of a number of parameters on the performance and sizing of the absorber (Blauwhoff et al., 1985; Rahimpour and Kashkooli, 2004; Bekassy-Molnar et al., 2005). The Henry’s law constant was established from equilibrium data, linearity of which is used to assess the suitability of equilibrium data for the design method adopted in this study. Figure 4 summarizes the equilibrium data which shows that the equilibrium curve is linear with a slope of 42.7 (mole fraction of SO₂ in air per mole fraction of SO₂ in water) with good fit ($R^2 = 0.9996$) (Nolan, 2000; Rubin et al., 2004).

Using mass balances, the minimum liquid flow rate was obtained from the slope of the minimum operating line $(L_m/G_m)_{min}$, that is 38.4. The slope of the actual operating line was obtained by multiplying $(L_m/G_m)_{min}$ by 1.5, giving $(L/G)_{actual} = 57.6$, so as to operate the absorber 50% above the equilibrium conditions. Figure 5 shows the actual and minimum operating lines on the y-x

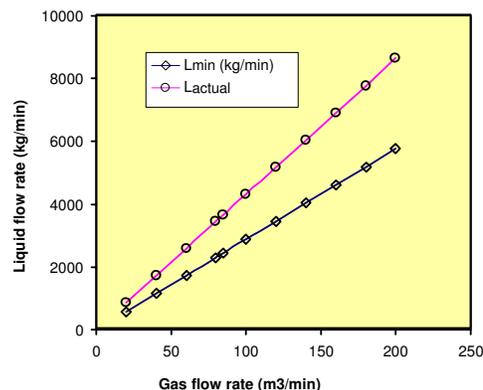


Figure 6. Comparison between minimum and actual solvent requirements for various gas flow rates.

diagram.

The effect of contaminated gas flow rate was studied by varying its flow rate between 20 and 200 m³/min to provide absorber designer with a wide range of data for sizing the equipment. The analytical procedure outlined in the modeling section was implemented, while varying the important parameters and examining their effect on the tower size and solvent requirements. In particular, the following parameters were studied:

- The effect of inlet gas flow rate**
- The effect of recycling spent solvent at increasing solute concentration, X_2**
- The effect of solute removal efficiency, E , on the solvent requirements and size of the tower**
- The effect of the percent flooding velocity, f , on tower size**
- The effect of packing characteristics (packing factor and size) on tower size.**

RESULTS AND DISCUSSION

Actual liquid flow rate

Figure 6 shows the comparison between the minimum

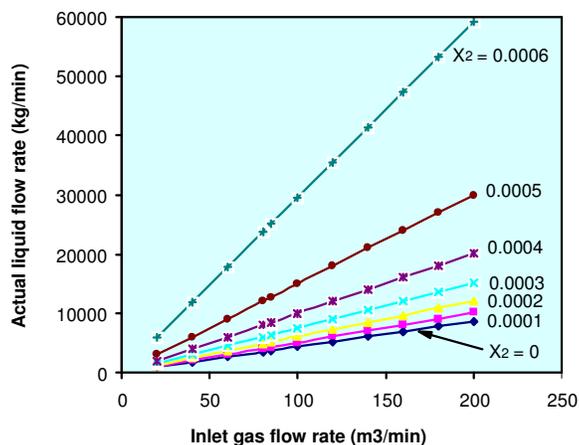


Figure 7. Variation of the actual liquid flow rate with inlet gas flow rate at various solute concentrations in the feed solvent ($X_2 = 0.07\%$, $E = 90\%$, $Y_1 = 3\%$).

and actual liquid flow rate into the absorption tower for various inlet gas flow rates. For the purpose of operating the tower away from equilibrium conditions, the solvent requirements, L_{actual} , increases. At any given inlet gas flow rate, if the tower is operated at L_{min} , the two phases will be at equilibrium, and mass transfer will be limited.

Beside its dependency on L/G ratio, the operating liquid flow rate depends strongly on the concentration of the solute as the liquid enters the absorber, X_2 . The L/G ratio illustrates a number of points about the choice of wet scrubbers used for gas absorption. For example, because flue gas desulfurization systems must deal with heavy particulate loadings, open, simple designs (such as venturi, spray chamber and moving bed) are used because packed towers can clog due to particulate matter collected. Also, the liquid-to-gas ratio for the absorption process is higher than for particle removal by scrubbing and gas velocities are kept low to enhance the absorption process.

Increasing the solute concentration, X_2 , the actual liquid flow rate required for 90% removal efficiency increases for all gas flow rate, as shown in Figure 7. This analysis was conducted at a fixed maximum concentration of the solute in the liquid, X_1 , of about 0.07%. It was observed that as X_2 approaches X_1 , the actual liquid requirements increase even further for the same inlet gas flow rate which is practically logical.

Figure 8 shows the variation of actual liquid flow rate with solute concentrations in the feed solvent at selected inlet gas flow rates. For all Q_g values, L_{actual} increases with X_2 . An abrupt increase in L_{actual} was observed when X_2 approaches X_1 . This can be attributed to the fact that as X_2 approaches X_1 then only a small amount of solute can be dissolved in the solvent, indicating that, in order to achieve the same absorption, more liquid is required. In other words, for effective absorption, there should be a wide range between X_1 and X_2 .

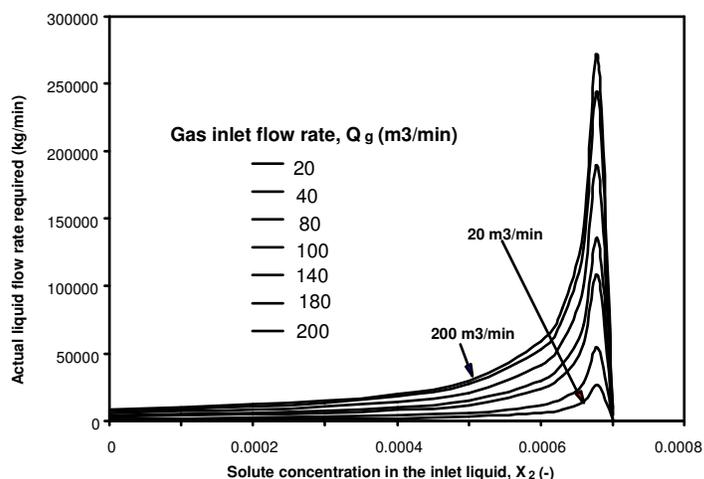


Figure 8. Effect of solute concentration in feed solvent on L_{actual} at various gas inlet flow rates.

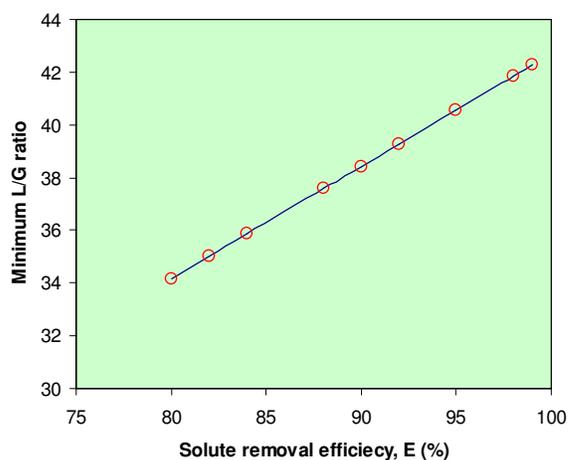


Figure 9. Variation of solute removal efficiency on the minimum L/G ratio.

Thus, there is a limited range to which solvent recycle can be allowed in the absorption process; otherwise intensive solvent use will be necessary. Continuous solvent recycle can only be achieved if the solvent is allowed to regenerate and lower the solute concentration.

Effect of the required absorption efficiency on operating conditions

The pre-set solute removal efficiency, E , affects the operating conditions of the absorption process. If all conditions remain constant, increasing E increases the minimum L/G ratio (as shown in Figure 9), indicating that

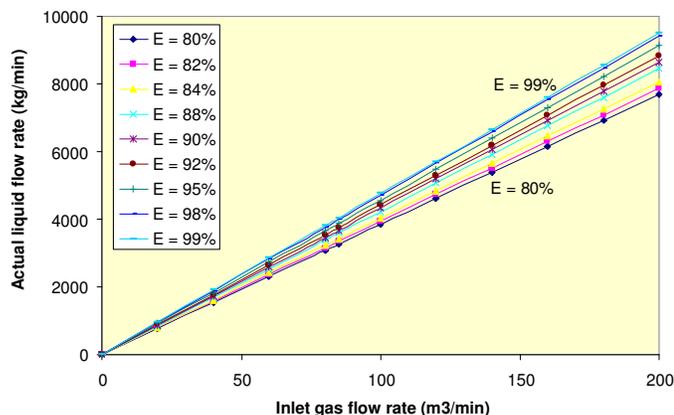


Figure 10. Effect of absorption efficiency on the actual solvent flow rate

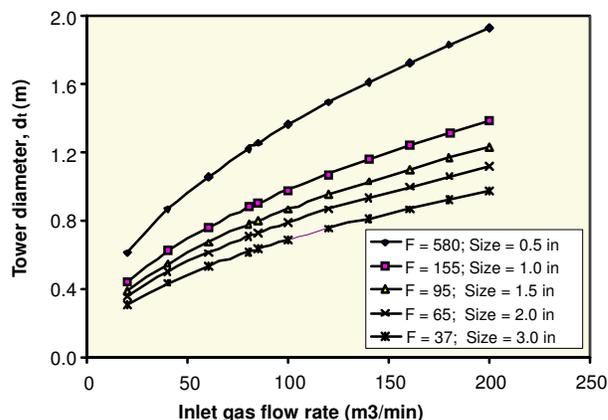


Figure 12. Effect of packing factor on the tower diameter.

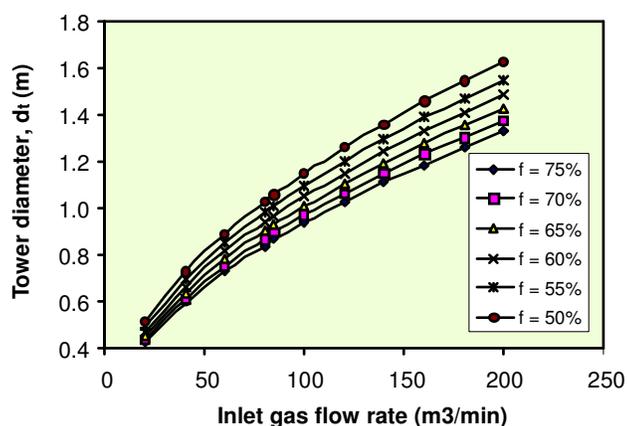


Figure 11. Effect of the percent of flooding velocity on the tower diameter.

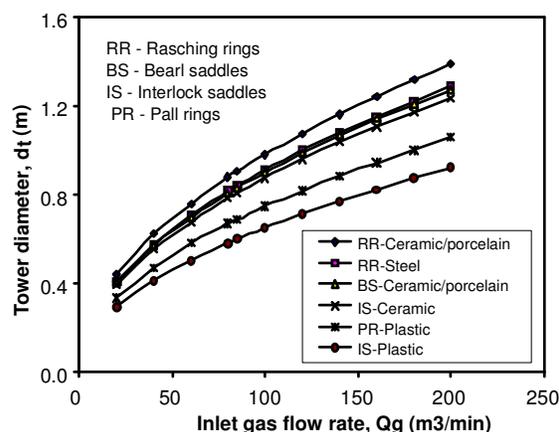


Figure 13. Dependency of tower diameter on the nature of packing materials.

the actual operating line equation will also have a high slope. High actual L/G ratio implies that more liquid is required for a given flow rate of gas to be treated to achieve a pre-set efficiency. Thus, setting a high E leads to higher solvent requirements during absorption which is expensive.

Figure 10 shows the variation of actual solvent flow rate with inlet gas flow rate at various absorption efficiencies for the same inlet and outlet conditions. Results show that the higher the absorption efficiency required the higher the actual solvent requirements for the same inlet gas flow rate, as depicted in Figure 10. However, the effect of E is negligible at lower inlet gas flow rates below 20 m³/min.

Factors affecting tower diameter

In general, the higher the inlet gas flow rate, the larger the tower diameter. Increasing the percent of flooding velocity (from 50 to 75%) the column diameter decreases

for the same inlet gas flow rate, as summarized in Figure 11. Thus, to minimize the cost of the absorber based on diameter, it is better to operate the absorption tower away from the flooding point.

Another factor influencing the tower diameter is the packing factor of the packing material used. For the same material type, the tower diameter required decreases with the packing factor. Based on packing factor data, whereby, the packing factor is inversely proportional to the packing size ($F_p = 89.4d_p^{-1.42}$), the tower diameter requirements decreases as size of packing material increases for the same inlet gas flow rate. The tower diameter data generated using (8) through 11 is presented in Figure 12.

For the same size of packing materials (1 inch) different packing materials have different packing factors due to differences in shapes. The F_p values of six different materials of the same size were used to determine absorber diameters using equations (8) through (11) as presented in Figure 13. The higher the packing factor the

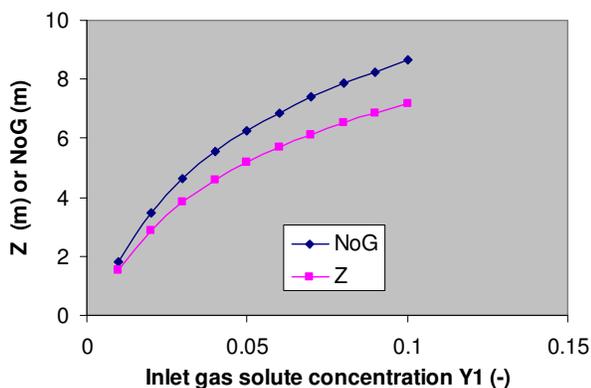


Figure 14. Variation of tower height with inlet solute concentration in the gas stream ($H_{OG} = 0.829$; $Y_1 = 0.03$; $Y_2 = 0.003$).

larger the tower diameter, as shown in Figure 13. All the materials selected were **1-inch** in size, but having different packing factors and surface area per unit volume. The Rasching rings made of ceramics or porcelain results in large tower diameter due to large packing factor. The Rasching rings made of different materials led to different tower diameters similar to those made of ceramic and steel. Similarly, Interlock saddles made of ceramic gives different d_t values from those made of plastic. Thus, packing material selection has an impact on the tower diameter sizing.

Absorption tower height

The number of transfer units, N_{OG} depends only on the inlet and outlet concentration of the solute. This is because in Equation (14) since Y_2 is normally fixed by the regulations on environmental pollution, then N_{OG} is only dependent on Y_1 and X_2 . For example, if the solute applies no partial pressure then m is very small ($m \rightarrow 0$) and Equation (14) becomes:

$$N_{OG} = \ln \frac{Y_1}{Y_2} \quad (15)$$

Therefore, achieving 90% removal of any toxic pollutant requires 2.3 transfer units. However, Equation (15) applies only when the equilibrium line is straight and the slope approaches zero (for very soluble or reactive gases). Figure 14 shows the variation of N_{OG} and Z with the solute concentration in the inlet gas, Y_1 . Increasing Y_1 was observed to increase the required tower diameter to achieve the same solute removal.

Similarly, increasing the solute removal efficiency, E ,

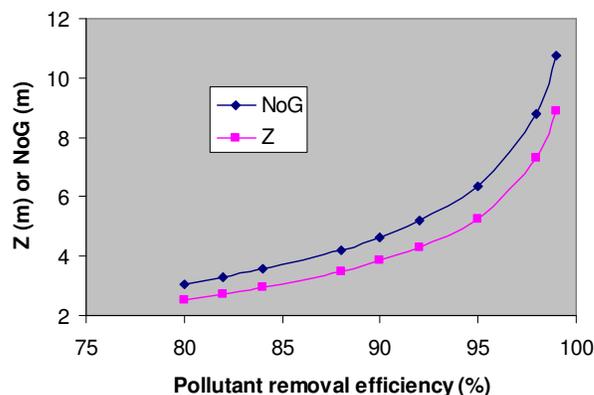


Figure 15. Variation of absorption tower height with toxic pollutant removal efficiency ($H_{OG} = 0.829$; $Y_1 = 0.03$).

while keeping other operating conditions constant, was observed to increase the required tower diameter as shown in Figure 15. As the removal efficiency approaches 100%, the tower diameter increases abruptly, showing that the cost of the equipment increases also when higher efficiency is required.

Note that the results shown in Figure 14 and 15 remain the same regardless of the inlet gas and solvent flow rates. Other factors controlling the tower height are surface area per unit volume of the packing (Equation 13), weight per unit volume of packing, and void fraction. However, only the packing factor is included in this design model for tower diameter (Equation 8). Moreover, during determination of the tower height, the specific surface area is not actually used in the modeling of tower height (Equations 12 and 13).

CONCLUSION

This paper shows that a computer model utilizing design equations for an absorber is capable of giving the designer with enough information for design of an absorber for a given inlet gas flow rate. The paper used the sample data of SO_2 as the solute in the exhaust air and being absorbed in water at an operating temperature of $30^\circ C$. The gas flow rate was varied from 20 to $200 \text{ m}^3/\text{min}$ from which the designer can select own flow rate and establish all necessary information for the tower: liquid flow rate, tower diameter and tower height. Simplifications based on experience were used to achieve reasonable design results. With this knowledge, the user of the model can design a tower for absorption of any toxic pollutant, as long as its equilibrium data in a selected solvent is available and gives a straight line on y - x diagram. In general terms, the aim is to use little solvent for treating a large volume of the gas which requires a solvent offering high solubility for the pollutant and operating the tower far away from the equilibrium

curve. Use of smaller amount of solvent will reduce the cost of solvent and pumping power (Thompson and King, 1987), equipment and capital costs. The solvent flow rate depends strongly on the inlet gas flow rate, concentration of solute in the inlet liquid, and required removal efficiency. The tower height depends only on the inlet liquid and gas conditions (Y_1 and X_2) and required removal efficiency, while it is independent of the flow rates of the fluids.

NOMENCLATURE

a	interfacial contact area (m^2)
F	packing factor
F	packing factor
f	the percent of flooding velocity (-)
G'	mass flow rate of gas per unit cross-sectional area of column (g/m^2s)
G'	mass flow rate of gas per unit cross-sectional area of column, $kg/m^2 s$
G	gas flow rate (m^3/s)
g_c	gravitational constant, $9.82 m/s^2$
G_m	gas molar flow rate ($kmol/h$)
H	Henry's law constant
H_{OG}	height of a transfer unit based on an overall gas-film coefficient (m)
H_{OL}	height of a transfer unit based on an overall liquid-film coefficient (m)
K_{OG}	overall mass-transfer coefficient based on the gas phase ($g\text{-mol}/h.m^2.Pa$)
L	liquid flow rate (kg/s)
L/G	liquid-to-gas ratio (-)
L_m	liquid molar flow rate ($kmol/h$)
N_{OG}	number of transfer units based on an overall gas-film coefficient, K_{OG}
N_{OL}	number of transfer units based on an overall liquid film coefficient, K_{OL}
P	pressure of the system (kPa)
P_{SO₂}	partial pressure of sulphur dioxide (Pa)
P_T	total pressure of the system (Pa)
x	mole fraction of solute in liquid phase (-)
X	mole ratio of the solute to the inert liquid (-)
y	mole fraction of solute in gas phase (-)
Y	mole ratio of the solute to inert gas (-)
Y*	toxic pollutant concentration in gas at equilibrium
Z	height of packing (m)
μ_l	viscosity of liquid (Ns/m^2)
ρ_g	density of the gas stream (kg/m^3)
ρ_l	density of the absorbing liquid, (kg/m^3)
φ	ratio of specific gravity of the scrubbing liquid to that of water

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