Flue-Gas Desulfurization ("Scrubbers")

(Nazaroff & Alvarez-Cohen, Section 7.C.2, much augmented)
(Mihelcic & Zimmerman, Section 12.8.2)

(Gongyi Lianghui Environmental Protection Machinery Equipment Factory)

Packed-bed scrubbers, also called *wet scrubbers* or *absorbing towers*, are pieces of equipment installed in power plants to remove selected gases (and sometimes also particulates) from combustion fumes in order to meet emission standards.

The usual gas being removed is SO_2, and we address here the design of a scrubber in this particular application.

The key aspect of the process is the dissolution of the gas from the fumes into a liquid made of water with suitable additives.
This process is called *stripping*.

The outflowing liquid is collected, concentrated, and recycled. Ultimately, the stripped gas ends up as a solid residue.

Example of post-operation pollution control (effluent treatment)

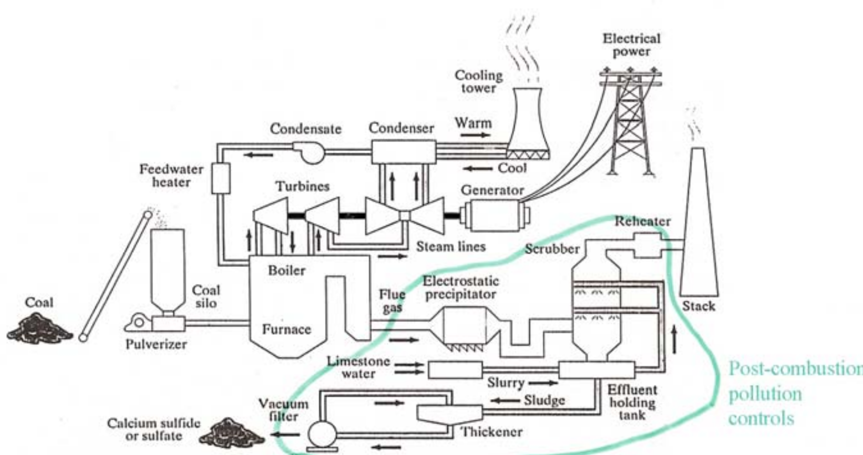


FIGURE 7.27. Typical modern coal-fired power plant using an electrostatic precipitator for particulate control and a limestone-based SO_2 scrubber. A cooling tower is shown for thermal pollution control.

As an aside:
Example of pre-operation pollution control (pollution prevention)

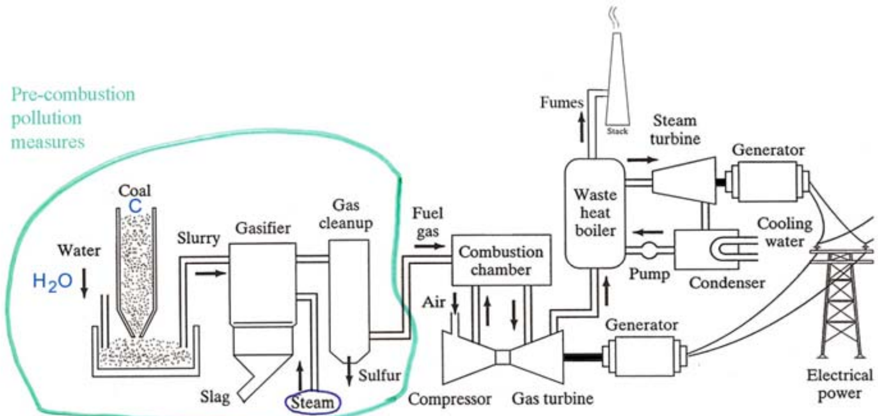
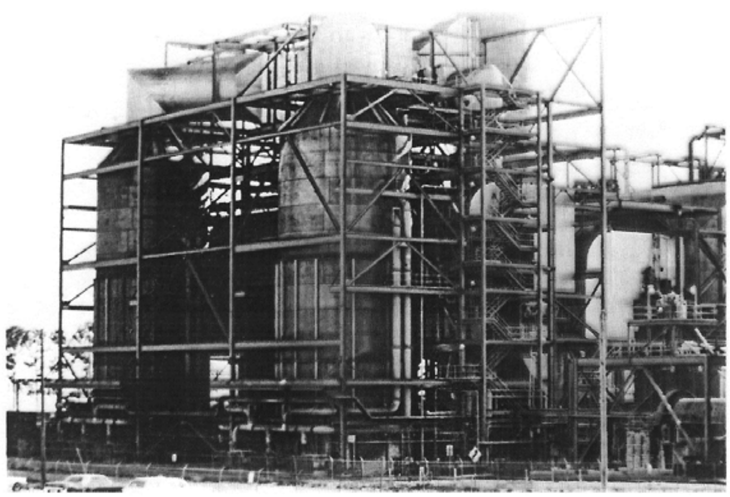


FIGURE 7.29 Integrated gasification combined cycle. Gasified coal fuels an efficient gas turbine; waste heat from the gas turbine powers a steam cycle.

In the gasifier: $C + \underset{\text{(from steam)}}{H_2O} + \text{heat} \longrightarrow CO + H_2$

Some scrubbers are large and costly to build. They are also costly to operate.



A limestone flue-gas desulfurization unit.
This unit treats approximately 1 million cubic feet of flue gas per minute from which it removes 85% of its SO_2.
Limestone use is about 100,000 tons per year.

Air-Cure Pte Ltd., Singapore

(http://www.ceilcoteapc.com.sg/spt-hrp_scrubbers.htm)

Smaller scrubber

This type of scrubber is most commonly used for the removal of noxious gases from airstreams. It is designed for high-efficiency collection and low-pressure drop. The vertical design has a relatively small footprint making it ideal for applications where floor space is at a premium.

Packed Tower Features:
- Capacity from 20 to 100,000 cfm
- High-efficiency packing for removal of soluble/reactive gases and liquid droplets down to 7 microns
- Lower portion of shell serving as integral sump for recycle liquid
- Single spray nozzle liquid distributor for minimum fouling

Applications:
- Scrubbing in semiconductor manufacturing
- Wastewater treatment odor control
- Acrylic acid scrubbing
- Foundry amine scrubbing
- NO_x control

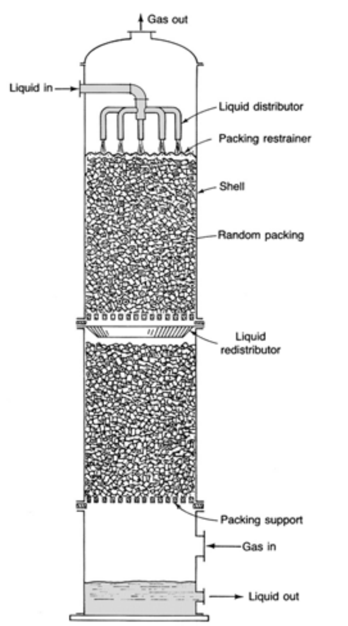
Inside look of a packed tower scrubber

In its essential aspect, a scrubber is a vertical tank (*tower*) in which gas and liquid flow against each other: The liquid solution flows downward while the gas bubbles to the top, each moved under the action of gravity.

To maximize contact between liquid and gas, the tower is also packed with a large number of small objects forcing the liquid to percolate slowly through tortuous paths and the gas to rise in small bubbles. As the liquid and gas compete for space, very intimate contact takes place between the two, and a very large contact area exists through which the transfer of chemical species can take place.

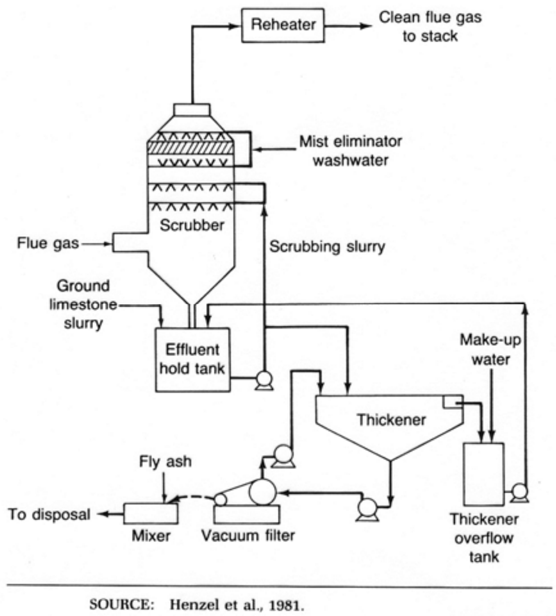
The counter flow with vapor moving upward and liquid downward is very practical for two reasons: (1) It happens naturally by gravity as the liquid trickles down while the gas bubbles up through it, and (2) the fumes encounter increasingly less loaded liquid as they get progressively cleaner on their way upward.

Schematic diagram of a packed gas absorption tower.



SOURCE: Treybal, R. E., *Mass Transfer Operations* (2nd ed.)
© 1968 McGraw-Hill.

How the equipment fits in the overall system



Once collected at the bottom, the laden solution (a Calcium solution in the case of SO_2) undergoes further reactions until a more valuable substance can be extracted, such as calcium sulfite ($CaSO_3$) or calcium sulfate ($CaSO_4$), which can be turned into plaster board.

The chemistry of desulfurization

The liquid used to “wash” the flue gas is a water-based calcium solution. Limestone ($CaCO_3$) is cheap and creates an alkaline environment in water:

$$CaCO_3 + H_2O \leftrightarrow Ca^{++} + HCO_3^- + OH^-$$

This OH^- radicals bind with SO_2 in solution to form a sulfur ion:

$$SO_2 + OH^- \leftrightarrow HSO_3^-$$

while water always dissociates a bit:

$$H_2O \leftrightarrow H^+ + OH^-$$

and while the bicarbonate HCO_3^- ions bind with H^+ to create H_2CO_3 (carbonic acid), which creates an equilibrium with water (H_2O) and carbon dioxide (CO_2):

$$HCO_3^- + H^+ \leftrightarrow H_2CO_3 \leftrightarrow H_2O + CO_2$$

Chemistry of desulfurization (cont'd)

The net result is the transformation of $CaCO_3$ to calcium ions (Ca^{++}), the release of carbon dioxide and production of HSO_3^- :

$$CaCO_3 + 2\,SO_2 + H_2O \leftrightarrow Ca^{++} + CO_2 + 2\,HSO_3^-$$

The carbon dioxide bubbles up as a gas, while HSO_3^- remains in the water solution (if the temperature is not too high – see final note below).

In the effluent hold tank, at the foot of the tower where the liquid is collected before final treatment, another load of limestone is added to the liquid, and a further reaction takes place:

$$CaCO_3 + 2\,HSO_3^- + Ca^{++} \rightarrow 2\,CaSO_3 \downarrow + CO_2 \uparrow + H_2O$$

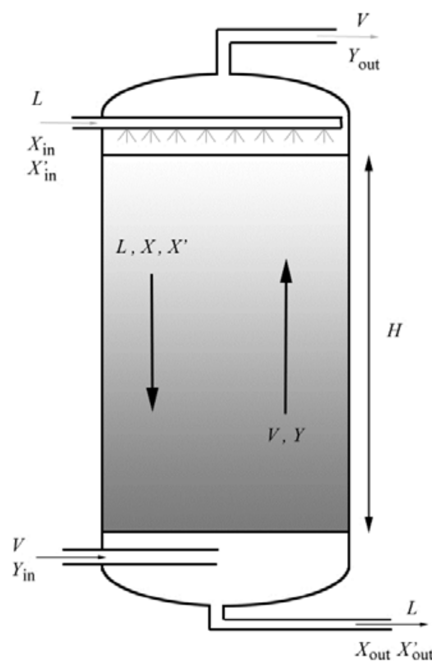
Calcium sulfite $CaSO_3$ is a solid precipitate. It is important to have the precipitation occur in the effluent hold tank rather than in the tower itself. Otherwise, the tower would become clogged. This is why the temperature and pH inside the tower need to be controlled.

Additional remarks

To ensure proper functioning, it is important to dose correctly the amount of limestone in the liquid fed at the top of the tower and to feed the remainder of the limestone to the effluent hold tank directly. The amount of limestone in the liquid is determined using stoichiometry (1 mole of $CaCO_3$ for 2 moles of SO_2, that is, 100 g of limestone per 128 g of sulfur dioxide removed from the flue gas) and is easily controlled by monitoring the pH, since it makes an alkaline solution.

The fact that some significant portion of the SO_2 in the liquid turns into another chemical, namely HSO_3^-, makes more room for SO_2 in the liquid and consequently promotes a greater suction of SO_2 from gas to liquid. When properly dosed, the limestone slurry is able to hold 6 to 15 times more S than pure water. This is very beneficial.

The central piece of equipment consists of a vertical tank, called tower, in which the fumes (vapor) are fed at the bottom, move upward through one or several layers of packed objects and exit at the top. Simultaneously, the cleaning liquid is poured from the top and trickles downward through the packed layers.



The variable are defined as:

X = number of moles of SO_2 in the liquid on a per-mass basis (moles per kg of liquid)
X' = number of moles of HSO_3^- in the liquid on a per-mass basis (moles per kg of liquid)
Y = number of moles of SO_2 in the vapor (fumes) on a per-mass basis (moles per kg of vapor)

L = mass flow of liquid trickling down (kg of liquid per minute)
V = mass flow of vapor bubbling upward (kg of vapor per minute)

H = height of the packed layers in the tower (meters)

The entrance and exit values are noted as:

Y_{in} = inlet value of Y (at bottom)
Y_{out} = exit value of Y (at the top)
X_{in}, X_{in}' = inlet values of X and X' (at the top)
X_{out}, X_{out}' = exit values of X and X' (at the bottom).

Since the vapor consists in the fumes coming from the combustion chamber, its chemical composition is known, and Y_{in} is therefore given.

Regulatory standards impose a certain level of cleanliness in the fumes released to the environment and therefore set the value of Y_{out}. Alternatively, one may impose a certain efficiency of removal (*ex.* η = 95%).

The efficiency η (sometimes called performance and denoted P) is defined as

$$\eta = 1 - \frac{Y_{out}}{Y_{in}}$$

Thus, Y_{out} is often set by the value of Y_{in} (fume composition) and η (required efficiency):

$$Y_{out} = (1-\eta)Y_{in}$$

To maximize the passage of SO_2 from vapor to liquid, we inject a clean liquid at the top and take $X_{in} = X_{in}' = 0$.

$$X_{in} = X_{in}' = 0$$

Finally, X_{out} and X_{out}' may be whatever we wish them to be. If at all possible, however, we would want to maximize them in order to minimize the amount of liquid being used (minimization of energy for pumping to the top of the tower and minimization of volume to be treated downstream of the tower).

The removal of SO_2 from the vapor and its dissolution into the liquid make the mass flow of vapor (V) decrease upward and the mass flow of liquid (L) increase downward, but these changes are negligible because the absolute mass of SO_2 being transferred is rather modest; the fume remains mostly air and CO_2, and the slurry remains mostly water.

We can then safely assume that the mass flow rates L and V stay at constant values throughout the tower:

$$L = \text{constant}$$
$$V = \text{constant}$$

Chemical equilibrium

Inside the liquid, a chemical equilibrium exists between the two forms of sulfur, SO_2 and HSO_3^-. Assuming first-order chemical kinetics, we can then state that there exists a proportionality between the two concentrations, namely:

$$X' = c\, X$$

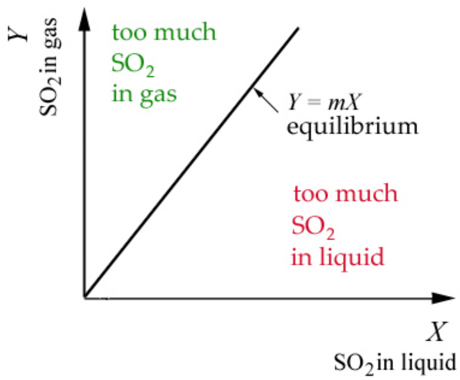
The coefficient c may be called the conversion factor. Its value ranges from 5 to about 14. Thus, the total amount of S in the solution is

which is 6 to 15 times what the amount would have been without the calcium additive.

Equilibrium line

At the interface between gas and liquid, SO_2 is exchanged between the two until equilibrium is achieved.
Equilibrium obeys Henry's Law of proportionality between gas and liquid phases:

$$Y = m\,X$$



At the temperature and pressure common in the operation of scrubbers, SO_2 equilibrium is achieved when the gas fraction is about 36 times the liquid fraction. Therefore, a practical value is

$$m = 36$$

The value of m varies with the nature of the gas being scrubbed and with temperature.
The value quoted here is strictly for SO_2 at around 40°C.
Should another gas be stripped (ex. H_2S), the m value may be very different.

Connection between the value of m and Henry's Law

Since the coefficient of proportionality m reflects a chemical equilibrium between (essentially) air and (essentially) water, it can be none other than a disguised form of the Henry's Law constant.

Henry's Law states: $P_{SO_2} = H\,[SO_2]$ with H = 0.81 atm/M at 25°C
= 1.05 atm/M at 40°C

In fumes (~ air):

$$Y = \frac{moles\ of\ SO_2}{grams\ of\ air} = \frac{moles\ of\ SO_2}{moles\ of\ air} \times \frac{moles\ of\ air}{grams\ of\ air} = \frac{P_{SO_2}}{P_{air}} \times \frac{1}{28.95\ grams/mole\ of\ air}$$

In liquid (~ water):

$$X = \frac{moles\ of\ SO_2}{grams\ of\ water} = \frac{moles\ of\ SO_2}{liters\ of\ water} \times \frac{liters\ of\ water}{grams\ of\ water} = [SO_2] \times \frac{1}{997\ grams/L\ of\ water}$$

Equilibrium: $Y = m\,X \Rightarrow \frac{P_{SO_2}}{P_{air}} \times \frac{1}{28.95\ g/mol} = m\,\frac{[SO_2]}{997\ g/L}$

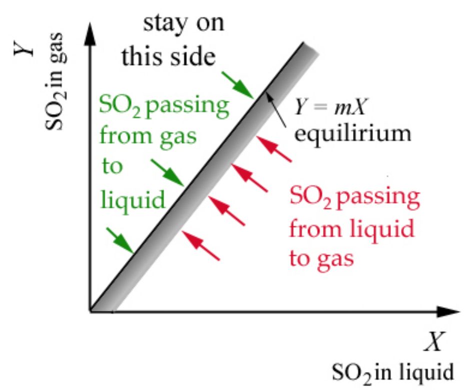
$$\Rightarrow m = \frac{997\ g/L}{28.95\ g/mol} \times \frac{P_{SO_2}}{[SO_2]} \times \frac{1}{P_{air}} = \frac{997\ mol/L}{28.95} \times \frac{H}{P_{air}} = 27.9 \text{ at 25°C and 1 atm}$$

$$= 36.1 \text{ at 40°C and 1 atm}$$

Gas-liquid transfer

The actual flow in the tower is not at equilibrium and a one-way exchange takes place.

It can be assumed that away from equilibrium, the transfer rate is proportional to the difference $Y - mX$, such that when $Y - mX$ is positive, there is an excess in the vapor phase and the transfer is from vapor to liquid (toward decreasing Y and increasing X), while when $Y - mX$ is negative, the transfer goes in the opposite direction. The transfer rate is furthermore proportional to the area of contact between gas and liquid. We model this as:



$$\text{transfer rate} = K\ A_c\ (Y - mX)$$

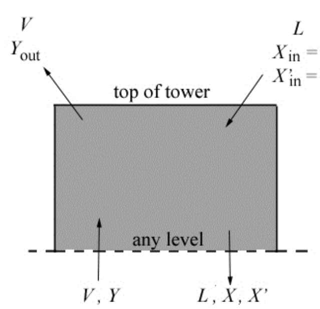
where K is a rate of transfer (mass per time and per area) and A_c is the area of contact between gas and liquid.

Mass balance from top downward

An important relation is obtained when we perform a mass balance for a section of the tower, from an arbitrary level to the top.

At the arbitrary level, the variables are Y, X and X', while at the top they are Y_{out}, X_{in} and X_{in}'.

Since the amount of entering sulfur is equal to that going out during steady operation, the sum of the influxes, VY from below and $L(X_{in} + X_{in}')$ from the top, must be equal to the sum of the effluxes, VY_{out} from the top and $L(X + X')$ from below:



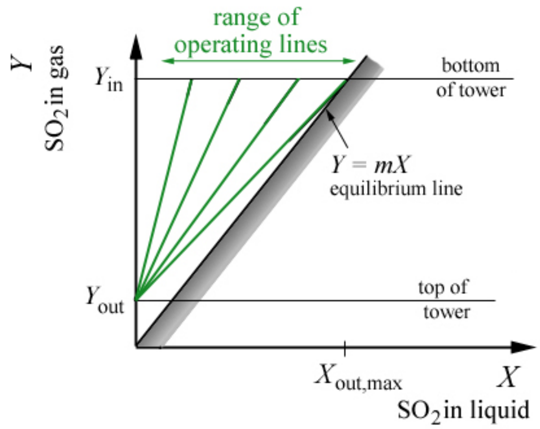
$$VY + L(X_{in} + X_{in}') = VY_{out} + L(X + X')$$

Since $X_{in} = 0$ and $X' = cX$, a division by V yields:

$$\boxed{Y = Y_{out} + (1+c)\frac{L}{V}X}$$

$$Y = Y_{out} + (1+c)\frac{L}{V}X$$

Operating line



On the X-Y plot, the previous relation corresponds to a straight line starting at ($X = 0$, $Y = Y_{out}$), corresponding to the top of the tower, and slanting upward with slope $(1+c)L/V$. This line is called the *operating line*.

At the top of the graph, where Y reaches its maximum value Y_{in}, which corresponds to the bottom of the tower, one obtains the value of X_{out} .

Since the amount of liquid used (L) is free to be chosen, we can consider a series of different operating lines, one for every slope $(1+c)\ L/V$ considered. In order to stay on the upper side of the equilibrium curve, however, there exits a minimum acceptable slope, and there is therefore a minimum value of the liquid mass flow, L_{min}, that must be used.

Minimum liquid needed

The maximum possible value of X_{out} is

$$X_{out.max} = \frac{1}{m}Y_{in}$$

which occurs when the liquid flowrate L is at its minimum allowed value

$$L_{min} = \frac{m}{1+c}\left(1-\frac{Y_{out}}{Y_{in}}\right)V = \frac{m}{1+c}\ \eta\ V$$

In practice, for a reason that will be become clear later in the analysis, one must stay clear from the minimum value and adopt for L a value that is a multiple of the minimum, namely:

$$1.5L_{min} \le L \le 3.0L_{min}$$

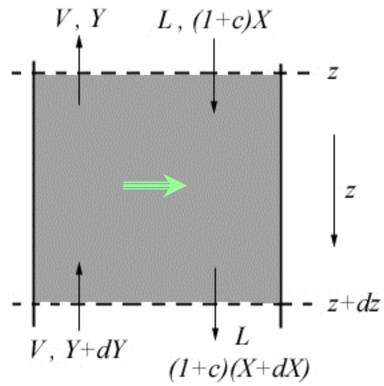
safety limit   wasteful beyond this

Separate mass balances

The operating line sets one relationship between the two variables, X and Y.

A separate mass balance must be performed for each independently in other to determine X and Y as functions of position inside the tower.

To do this, we now consider a thin slice of the packing inside the tower, from the level z to the level $z + dz$, counting z downward from the top ($z = 0$ where $Y = Y_{out}$ and $X = X_{in} = 0$).



The steady-state budgets express that the rate at which the amount in each phase (gas or liquid) enters the slice is equal to the rate at which it exits plus or minus the amount exchanged with the other phase:

$$V(\cancel{Y} + dY) = \cancel{VY} + K\ dA_c (Y - mX)$$
$$L\ (1 + c)\cancel{X} + K\ dA_c (Y - mX) = L\ (1 + c)(\cancel{X} + dX)$$

where dA_c is the contact surface area between liquid and gas within the small volume.

Contact area – Differential equations

If we define *a* as the surface *area* made available by the packed objects *per volume* of packing (in ft² per ft³), then dA_c is equal to *a* times the volume of the slice.

If $A = \pi d^2/4$ is the cross-sectional area of the tower of inner diameter d, this volume is Adz, and the contact area in that volume is

$$dA_c = a\,A\,dz$$

The previous budget equations become:

$$V\,dY = +K\,a\,A\,(Y - mX)\,dz$$

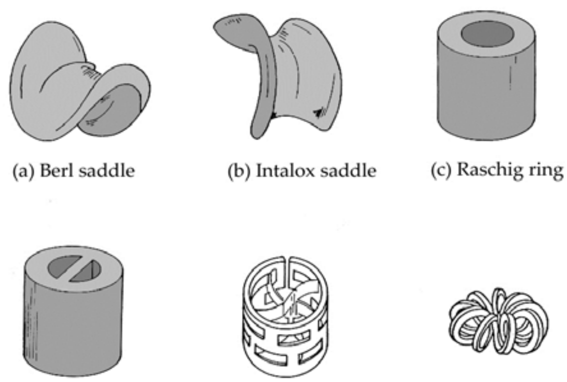
$$(1+c)L\,dX = +K\,a\,A(Y - mX)\,dz$$

Or, in the form of differential equations:

$$\boxed{\begin{aligned} \frac{dY}{dz} &= \frac{KaA}{V}(Y - mX) \\ \frac{dX}{dz} &= \frac{KaA}{(1+c)L}(Y - mX) \end{aligned}}$$

Types of packing elements

Typical tower packings



(a) Berl saddle (b) Intalox saddle (c) Raschig ring

(d) Lessing ring (e) Pall ring (f) Tellerette

Variations of Tellerette type

These elements are designed to create tortuous flow paths in order to maximize contact between gas and liquid.

Table 13.4 Tower Packing Characteristics

Type	Material	Nominal Size, in.	Bulk Density,† lb_m/ft^3	Total Area,† ft^2/ft^3 (a)	Porosity ϵ	Packing Factors‡ F_p	f_p
Berl saddles	Ceramic	$\frac{1}{2}$	54	142	0.62	240	§1.58
		1	45	76	0.68	110	§1.36
		$1\frac{1}{2}$	40	46	0.71	65	§1.07
Intalox saddles	Ceramic	$\frac{1}{2}$	46	190	0.71	200	2.27
		1	42	78	0.73	92	1.54
		$1\frac{1}{2}$	39	59	0.76	52	1.18
		2	38	36	0.76	40	1.0
		3	36	28	0.79	22	0.64
Raschig rings	Ceramic	$\frac{1}{2}$	55	112	0.64	580	§1.52
		1	42	58	0.74	155	§1.36
		$1\frac{1}{2}$	43	37	0.73	95	1.0
		2	41	28	0.74	65	§0.92
Pall rings	Steel	1	30	63	0.94	48	1.54
		$1\frac{1}{2}$	24	39	0.95	28	1.36
		2	22	31	0.96	20	1.09
	Polypropylene	1	5.5	63	0.90	52	1.36
		$1\frac{1}{2}$	4.8	39	0.91	40	1.18

† Bulk density and total area are given per unit volume of column.
‡ Factor F_p is a pressure-drop factor and f_p a relative mass-transfer coefficient.
§ Based on NH_3–H_2O data; other factors based on CO_2–NaOH data.

SOURCE: McCabe, W. L., Smith, J. C., and Harriott, D., *Unit Operations of Chemical Engineering*, © 1985 McGraw-Hill, Inc. Used by permission.

Since the operating line sets a relationship between Y and X, we can replace Y in terms of X in the second equation to obtain a single equation for the variable X:

$$\frac{dX}{dz} = \frac{KaA}{(1+c)L} Y_{\text{out}} + \underbrace{\boxed{\frac{KaA\,[(1+c)L - mV\,]}{(1+c)LV}}}_{\lambda} X$$

Integration from the top (where $X = 0$ at $z = 0$) downward ($z > 0$) yields:

$$X(z) = \frac{V(e^{\lambda z} - 1)}{(1+c)L - mV} Y_{\text{out}}$$

where the coefficient λ in the exponent is defined as

$$\lambda = \frac{KaA[(1+c)L - mV\,]}{(1+c)LV} > 0$$

The accompanying solution for Y is:

$$Y(z) = \frac{(1+c)Le^{\lambda z} - mV}{(1+c)L - mV} Y_{\text{out}}$$

From this, we can determine the values at the bottom.

If H is the height of the packed layer inside the tower where the gas-to-liquid exchange takes place, the bottom values are obtained for $z = H$:

$$X_{\text{out}} = \frac{V(e^{\lambda H} - 1)}{(1+c)L - mV} Y_{\text{out}}$$

Since the Y_{in} value is known, the last equation sets a constraint on the dimensions of the tower:

$$Y_{\text{in}} = \frac{(1+c)Le^{\lambda H} - mV}{(1+c)L - mV} Y_{\text{out}}$$

$$\Rightarrow \quad H = \frac{1}{\lambda} \ln\left[\left(1 - \frac{m}{1+c}\frac{V}{L}\right)\frac{Y_{\text{in}}}{Y_{\text{out}}} + \frac{m}{1+c}\frac{V}{L}\right]$$

More practical notation

Define

1) the auxiliary parameter $\beta = \dfrac{mV}{(1+c)L} = \dfrac{1}{\eta}\dfrac{L_{\min}}{L}$

2) the number $N = \dfrac{\ln\left(\dfrac{1-\eta\beta}{1-\eta}\right)}{1-\beta}$ (not necessarily an integer)

3) the so-called *height of a transfer unit* $HTU = \dfrac{V}{KaA}$

With this, the expression for the height H of the tower becomes

$$\boxed{H = N \times HTU}$$

A couple of remarks

Because a greater gas velocity promotes better contact, the density of contact area a is somewhat dependent on the gas velocity v, and it is often impractical to try to estimate HTU from its separate ingredients.
In many applications, therefore, the value of HTU is often determined experimentally.

Note that, in any event, the value of HTU does not depend on the overall dimensions of the tower and absolute flow rates, but only on local variables, such as K, a and v.

We can also see now why the liquid flow rate L may not be taken at its minimum value $L_{\min}$.

If it were ($L = L_{\min}$), the number of steps would be infinite and the required tower height would be infinity! ($N \to \infty$ as $\beta \to \beta_{\max} = mV/(1+c)L_{\min} = 1/\eta$).

This is why the actual liquid flow rate needs to be greater than the minimum value.

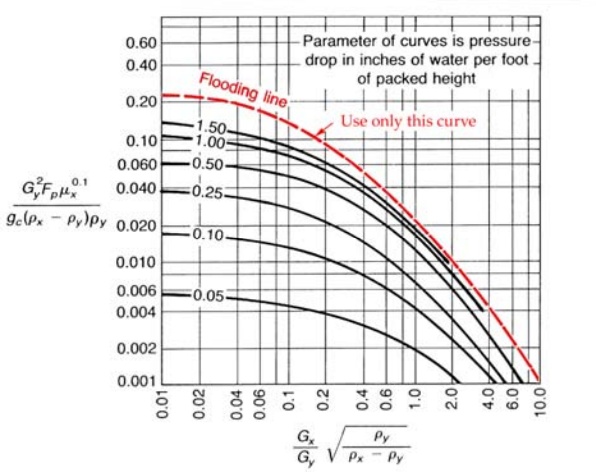
Watch out for flooding!

To reduce the diameter of the tower and therefore the cost, one wishes to pass the required liquid and gas flows through the narrowest possible section, that is, at the highest possible speeds.

There is, however, a limit on the gas velocity. If the gas velocity exceeds a certain threshold, it literally blows the liquid away from the packing material and prevents it from trickling downward. The result is an accumulation of liquid above the packed layers and flooding in the upper section of the tower.

To determine the safest possible gas speed, the procedure is to calculate the flooding speed and then take a fraction of the latter.

Generalized correlation for flooding and pressure drop in packed towers.



SOURCE: McCabe, W. L., Smith, J. C., and Harriott, D., *Unit Operations of Chemical Engineering*, © 1985 McGraw-Hill, Inc.

Variables used in connection with this graph:

F_p = packing factor (see earlier slide)
ρ_x = liquid density (in lbm/ft^3)
ρ_y = gas density (in lbm/ft^3)
μ_x = 0.80 cp, liquid viscosity
g_c = 32.17 ft.lbm/s^2.lbf gravitational constant

$G_x = L/A$ = liquid mass flux (in lbm/ft^2.s)
$G_y = V/A$ = gas mass flux (in lbm/ft^2.s)

The flooding speed is determined from the top curve of the graph shown on the previous slide.

The abscissa is first calculated using the already known gas and liquid mass fluxes (noting that G_x/G_y is equal to L/V) and the densities of both liquid (ρ_x) and gas (ρ_y).

From the abscissa, one goes up the graph to the top, dashed curve - labeled "Flooding line" - and across to determine the corresponding ordinate.

This is rather complicated, especially because of the antiquated units and the introduction of new variables such as G_x and G_y. Better is to use the same information in a tabulated form, with variables expressed in metric units, as done on the next slide.

To facilitate the calculations, here are flooding values tabulated in terms of original variables and in metric units:

$\frac{L}{V}\sqrt{\frac{\rho_y}{\rho_x-\rho_y}}$	$\frac{F_p V^2}{(\rho_x-\rho_y)\rho_y A^2}$	$\frac{L}{V}\sqrt{\frac{\rho_y}{\rho_x-\rho_y}}$	$\frac{F_p V^2}{(\rho_x-\rho_y)\rho_y A^2}$
0.010	0.718	0.40	0.161
0.015	0.682	0.50	0.131
0.02	0.642	0.60	0.113
0.03	0.617	0.80	0.0871
0.04	0.599	1.0	0.0663
0.05	0.581	1.5	0.0474
0.06	0.526	2.0	0.0306
0.08	0.461	3.0	0.0183
0.10	0.437	4.0	0.0131
0.15	0.355	5.0	0.00886
0.20	0.275	6.0	0.00703
0.30	0.197	8.0	0.00458
	in m^2/s^2	10.0	0.00306

Here, densities ρ_x and ρ_y are in kg/m^3 while flow rates L and V are in kg/s .
The area A is in m^2. The packing factor F_p is dimensionless (see earlier table).

In the expression tabulated in the right column, all factors should be known except the tower's cross-sectional area A. Thus, reading the value in the right column provides a value for $A_{flooding}$ at the flooding limit.

The recommended operational area is twice the value at the flooding limit. Thus:

$$A = 0.5\ A_{\text{flooding}}$$

The required inner diameter of the tower D is calculated (using $A = \pi\ D^2/4$). Thus,

$$D = \sqrt{\frac{4V}{\pi \rho_y v}}$$

A Final Note

The fumes exiting the furnace are hot and need to be cooled significantly before entering the scrubber. This is necessary to reduce the volatility of HSO_3^- (into which SO_2 turns once in the liquid phase) and therefore to promote its retention into the liquid used for the scrubbing.

Reheating the cleaned fumes is necessary afterwards for more efficient release through the smokestack to the atmosphere.

Recapitulation of the design procedure

- Establish the expected performance $P = \eta = 1 - Y_{out}/Y_{in}$.
- From Y_{in}, Y_{out} and the equilibrium line, determine L_{min}, paying attention to the factor $(1+c)$ in order to take into account the chemical changes of SO_2.
- From L_{min}, set the L value using the rule $1.5\ L_{min} \leq L \leq 3.0\ L_{min}$.
- Determine the value of the parameter $\beta = mV/(1+c)L$.
- Calculate the number N of stages, using its expression in terms of η and β.
- Select or estimate a value for the height of a transfer unit (HTU).
- Determine the tower height $H = N$ x HTU.
- Determine the cross-sectional A *at* flooding.
- Set the cross-sectional area A at twice the value at flooding.
- Determine the tower diameter D.
- Estimate the amount of limestone needed.

An example

Given:

Flue gas flow of 10,000 ft^3/min at T = 49^{o}C and p = 1 atm
Incoming SO_2 concentration is 0.30%
Assume an empirical multiplier value $c = 6$
Criterion for liquid flow is $L = 1.8\ L_{min}$
Packing with 1.5-in Berl saddles
HTU = 14 ft

Objective:

Remove 95% of the SO_2

Question:

What should be the dimensions (height and inner diameter) of the tower?

Solution:

Start by finding Y_{in} and Y_{out}:

0.30% of moles of SO_2 per mole of air → Y_{in} = 3 x 10^{-3} moles SO_2/mole air

Since 1 mole of air weighs 28.8 g = 28.8 x 10^{-3} kg
→ Y_{in} = 3 x 10^{-3} /28.8 x 10^{-3} = 0.104 moles SO_2/kg air

95% reduction required → Y_{out} = 5% of Y_{in} → Y_{out} = 5.21 x 10^{-3} moles SO_2/kg air

Next put the gas flow rate in the required units (volume per time → mass per time)

At 49°C = 322.15 K and 1 atm, volume of one mole of air is RT/p = 0.0264 m³,
corresponding to a density of 0.0288 kg / 0.0264 m³ = 1.09 kg/m³

The gas flow rate is 10,000 ft³/min = 283.3 m³/min → V = 308.7 kg/min

Now, we can determine the minimum amount of liquid required:

$$L_{min} = \frac{m}{1+c}\left(1-\frac{Y_{out}}{Y_{in}}\right)V = \frac{36}{1+6}(0.95)(308.7\ \mathrm{kg/min}) = 1508\ \mathrm{kg/min}$$

From this follows the actual liquid flowrate to be used:

$$L = 1.8\ L_{min} = 2714\ \text{ kg/min}$$

Next we determine the parameter β

$$\beta = \frac{mV}{(1+c)L} = \frac{36\times 308.7\ \text{kg/min}}{(1+6)\times 2714\ \text{ kg/min}} = 0.585$$

from which follows the number of HTUs needed

$$N = \frac{\ln\left(\frac{1-\eta\beta}{1-\eta}\right)}{1-\beta} = 5.26$$

Since we are given the height of the HTU, we immediately get the height of the tower:

$$HTU = 14\ \text{ft} \quad\rightarrow\quad H = N\times HTU = 5.26\times 14\,\text{ft} = 73.7\,\text{ft} = 22.5\text{m}$$

The diameter of the tower is obtained by keeping a safety margin from flooding. For this, we calculate the following quantities:

$$\frac{L}{V} = \frac{2714}{308.7} = 8.794$$

$$\rho_y = 1.09 \text{ kg/m}^3 = 0.0679 \text{ lbm/ft}^3$$

$$\rho_x \cong 1000 \text{ kg/m}^3 = 62.32 \text{ lbm/ft}^3$$

$$\Rightarrow \frac{L}{V}\sqrt{\frac{\rho_y}{\rho_x - \rho_y}} = 0.290$$

Consult table and find by interpolation:

$$\frac{F_p V^2}{(\rho_x - \rho_y)\rho_y A^2} = 0.205 \frac{m^2}{s^2}$$

Berl saddles 1.5-in size → $F_p = 65$

$$\Rightarrow A_{flooding} = V\sqrt{\frac{F_p}{0.205(\rho_x - \rho_y)\rho_y}}$$

$$= 166.6\, m^2$$

For effective operation, operate at twice the flooding area:

$$A = 2A_{flooding} = 333.2 \text{ m}^2$$

Finally, determine the tower diameter from the required cross-sectional are:

$$A = \frac{\pi}{4}D^2 \quad \rightarrow \quad D = \sqrt{\frac{4A}{\pi}} = 20.6 \text{ /// } 2.73 \text{ m}$$

Done !!!

We were able to get rid of 95% of the SO_2!

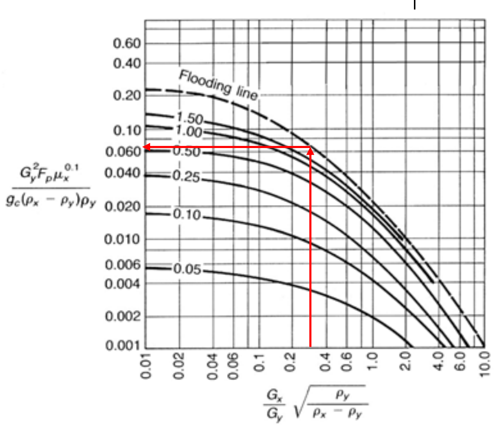
The diameter of the tower is obtained by keeping a safety margin from flooding.
So, we calculate the quantities needed to use the flooding curve.

$$\frac{G_x}{G_y} = \frac{L}{V} = \frac{2714}{308.7} = 8.794$$

$$\rho_y = 1.09 \text{ kg/m}^3 = 0.0679 \text{ lbm/ft}^3$$

$$\rho_x \cong 1000 \text{ kg/m}^3 = 62.32 \text{ lbm/ft}^3$$

$$\Rightarrow \quad \frac{G_x}{G_y}\sqrt{\frac{\rho_y}{\rho_x - \rho_y}} = 0.290$$



$$\frac{G_y^2 F_p \mu_x^{0.1}}{g_c(\rho_x - \rho_y)\rho_y} = 0.060$$

Berl saddles 1.5-in size → F_p = 65

$$\frac{G_y^2(65)(0.80)^{0.1}}{(32.17)(62.32-0.0679)(0.0679)} = 0.060$$

$$G_y^2 = 0.128 \quad \rightarrow \quad G_y = 0.358\,\text{lbm/ft}^2\cdot\text{s} = 1.752\,\text{kg/m}^2\cdot\text{s}$$

For effective operation, operate at 50% of flooding velocity:

$$G_y = \frac{1}{2}\times 1.752\,\text{kg/m}^2\cdot\text{s} = 0.876\,\text{kg/m}^2\cdot\text{s}$$

From this follows the gas velocity

$$v_y = \frac{G_y}{\rho_y} = \frac{0.876\,\text{kg/m}^2\text{.s}}{1.09\,\text{kg/m}^3} = 0.804\,\text{m/s} = 48.24\,\text{m/min}$$