**Paper 7A**

# "A DESIGN REVIEW OF STEAM STRIPPING COLUMNS FOR WASTEWATER SERVICE"

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**ABSTRACT**

In recent years the role of steam strippers in industry has become an integral part of plant operations. The goal when designing these types of columns is to have reliable operation for as long as possible. In order to achieve this goal the designs of these columns have to be carefully considered. The author will detail the methodology used when designing steam strippers for wastewater service. Some of the topics that will be covered by the author are:

1. Steam Stripper Design Fundamentals.
2. The importance Process Chemistry has on the column design.
3. Operation of a steam stripper.
4. How to select internals for a steam stripper column.

The author will present an example of a steam stripper design.

## Introduction

Steam stripping for wastewater purification is a distillation process where light volatile organics are removed from water (A heavier component). The volatile organics present in the feed stream to these types of columns are usually in low concentrations in comparison to the water phase. The typical organics present are as follows:

1. Benzene
2. Toluene
3. M-P-O Xylene
4. Ethyl benzene
5. Styrene
6. Chlorinated Hydrocarbons

*This list may change depending on the service.*

Steam stripping takes place at high temperatures that are usually very close to the boiling point of water.

The removal of volatile organics is a strong function of temperature. Steam stripping allows for the removal of heavy soluble organics that other stripping techniques will not remove (Air, etc).

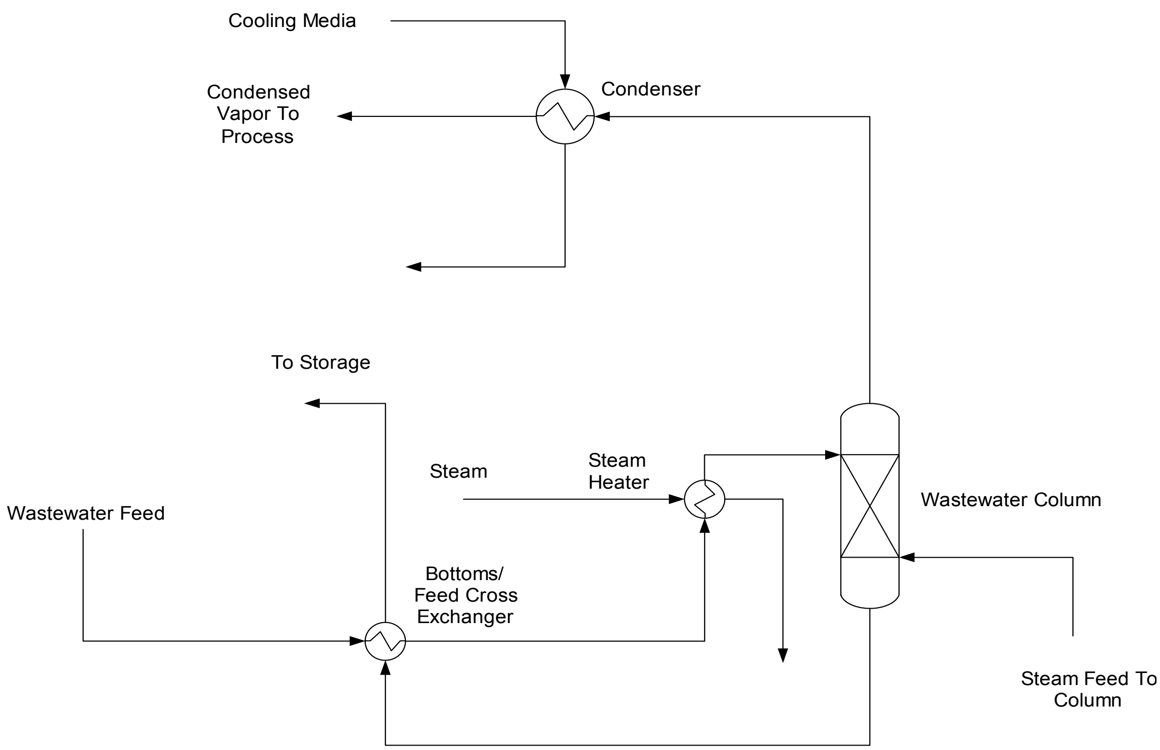
The typical arrangement of a steam-stripping column is a column where the liquid feed is introduced at the top of the column while steam is introduced at the bottom of the column. The wastewater feed stream is heated and put in contact with steam in a packed or trayed tower (**FIGURE 1**).

The combined effects of the steam and heat cause organic material to transfer from the liquid phase to the vapor phase. The steam-stripping tower utilizes trays or packing internals to facilitate contact between the contaminated water stream and the steam stream. The volatile organic material is then carried out with the vapor. As contacting proceeds down the column, the wastewater becomes leaner with organic material while the vapor phase becomes more enriched with organic material as it travels up the column.

The overhead organic vapor that comes off the top of the column is condensed and recovered. The recovered hydrocarbons can either be treated with an incinerator or recycled back into the process. The purified water that comes off the bottom of the column can be recycled back into the plant's water system.

Steam stripping in wastewater service offers high VOC recovery. (Greater than 99%) The purified water at the bottom of the column has very low contaminate concentrations. (6)

Figure 1 - Typical Wastewater System




## TOWER DESIGN

When a steam-stripping column is being designed it is necessary to set the values for a complete set of independent variables. The feed variables are normally already known; therefore, it is typically necessary to pick near-optimum values for the gas-to-liquid ratio, column pressure, column diameter, and the product purity. From this set of independent variables, it is possible to determine the number of theoretical stages needed to achieve the desired separation.

### Feed Stream

It is very importance that when designing a steam stripper that the designer has a complete understanding of the chemistry of the feed stream. A lack of understanding of the chemistry of the feed stream can lead to an improper design of the column. It may also lead to operability and maintenance problems. Some of the problems that can result from a poor understanding of feed composition are as follows:

1. Incorrect material selection for internals and piping. This could lead to problems like stress corrosion cracking and other forms of material attack. (**Figure 2)** The

material of construction must be considered carefully due to the dynamic nature of the composition of most wastewater streams.

2. Loss of operational capacity due to foaming.
3. Column fouling and plugging due to solid precipitation (Salts, etc.).
4. Reduction in column efficiency because of incorrect operational parameter design. Specifically, if the wrong concentration of organic material is used to design the column if could affect how much steam is used in the column. If the column is not designed with enough steam capacity there may not be enough heat to drive of the saturated organics to the design point of the column.

The characteristics of the feed stream must first be determined before any design work begins. This includes any possible composition variations that might occur.

**Column Pressure**

The operating pressure of a steam stripper can influence the efficiency and reliability of the column. For example, the lower the operating pressure the better the volatility achieved. Lower operating pressures will also result in lower operating temperatures. Stream strippers operating at vacuum pressure can be highly efficient. Operating at vacuum pressures also allows the use of plastic internals to combat the effects of corrosive systems. (6) The drawback of operating at vacuum conditions is the added expense of the operation and maintenance of vacuum equipment (ejectors/pumps).

Typically most steam strippers are designed at or near atmospheric operating pressure. Operating at or near atmospheric pressure allows the designer to take advantage of higher volatilities and lower operating temperatures without having the added expense of operating vacuum equipment.

**Figure 2**

**Figure 2** – This is the picture of a tray that has been damaged by temperature-induced corrosion.

However, if the column's operating pressure is increased there are some unfavorable effects.

1. Raising the pressure increases the solubility of the solute and increases the separation difficulty.

2. More steam input into the column is required to achieve the same separation efficiency.

3. Raising the column's pressure may induce organic salt precipitation.

If the column pressure chosen results in the flashing of the feed liquid inside the tower, this effect must be accounted for in the design of the upper section internals in order to avoid overloading and flooding near the top of the tower.(1)

**Column Feed Pre-Heat**

Preheating the feed before it is introduced into the column is important because it reduces the amount of heat added to the column to achieve the desired separation. The feed can be heated in several different ways.

1. A heat recovery exchanger that cross exchanges the feed with the effluent coming off the bottom of the column.
2. A steam heat exchanger that cross exchanges the feed with a steam stream.
3. Depending how much heat is needed it may be required to have a combination of a recovery exchanger and a steam heat exchanger.

Due to the fouling nature of most wastewater systems the design of the feed pre-heat system should allow frequent cleaning. Typically a set of redundant exchangers are installed to allow for on-line cleaning of pre-heat exchangers.

**Column Design Equations (Importance of Design Diagrams)**

The gas stream at any point in a stripper consists of the following: (3)

G total mol/(Tower Area)(Time)
y - mole fraction
A – Diffusing solute
p – Partial Pressure
$p_t$ – Total Pressure
$G_S$ nondiffusing gas mol/(Tower Area)(Time)
Y – Mole Ratio

The equations governing the relationship are as follows:

$Y = y/(1-y) = p/(p_t - p)$

$G_S = G(1\text{-}y) = G/(1+Y)$

The liquid stream consists of L total mol/(Tower Area)(Time). The stream contains the following: (3)

x - mole fraction
L – Total mol/(Tower Area)(Time)
$L_S$ – Nonvolatile Solvent mol/(Tower Area)(Time)
X – Mole Ratio

The equations governing the relationship are as follows:

$X = x/(1\text{-}x)$

$L_S = L(1\text{-}x) = L/(1+X)$

**Equilibrium Curve:**

During the design phase of a stripper one of the first things that should be done is to collect accurate and reliable equilibrium data. Thermodynamic models are used to help determine the total number of transfer units and the height of transfer unit. (6)

When designing steam strippers a base line thermodynamic model that can be used is Henry's law,

$yP = Hx$.

P – Total Pressure
x – Liquid Mole Fraction
y – Vapor Mole Fraction
H – Henry Constant

Accurate Henry's constants are not easy to obtain. There are several factors that come into play to determine the value of Henry's constants.

1. Composition of components in the water phase.
2. Temperature
3. Inorganic contaminants

Typically the best type of thermodynamic equation to use for steam strippers is one that uses activity coefficients that can predict immiscibility (Non-Ideal Conditions). Stripper feeds can contain materials like insoluble salts and other inorganics that tend to make these streams non-ideal.

Activity coefficient models can be used for liquid mixtures of all species. Activity coefficient models do not incorporate the density of the liquid and does not do a good job of describing an expanded liquid that occurs near the vapor liquid critical point of the mixture. Problems can also occur when using two different models for the liquid phase and the vapor phase. For example, when using an activity coefficient model for the liquid phase and an equation of state for the vapor phase the properties of the two phases may not become identical. When this occurs the vapor liquid critical region behavior is predicted incorrectly.

**Activity Coefficient Method**

An ideal mixture can either be liquid or gaseous which is defined by the following relationships:

$$\underline{H}_i^{IM}(T,P,x_i) = \underline{H}_i(T,P)$$
$$\overline{V}_i^{IM}(T,P,x_i) = \overline{V}_i(T,P)$$

Where: T- temperature, °F
P- pressure, psia
$x_i$- liquid phase mole fraction
$\overline{V}_i$ - Partial Molar Volume, $i^{th}$ Component
$\underline{H}_i$ - Enthalpy Per Mole, $i^{th}$ Component
$\underline{H}_i^{IM}$ - Enthalpy Per Mole, Ideal Mixture
$\overline{V}_i^{IM}$ - Partial Molar Volume, ideal Mixture

In an ideal liquid solution, the liquid fugacity of each component in the mixture is directly proportional to the mole fraction of the component. The ideal solution assumes that all molecules in the liquid solution are identical in size and are randomly distributed. This assumption is valid for mixtures containing molecules of similar size and character. (8)

In general, you can expect non-ideality in mixtures of unlike molecules. Either the size or shape or the intermolecular interactions between components may be dissimilar. These differences are called size and energy asymmetry. Energy asymmetry occurs between polar and non-polar molecules and also between different polar molecules. An example is a mixture of alcohol and water. (8)

The activity coefficient represents the deviation of the mixture from ideality. The activity of a component at some temperature, pressure and composition is defined as the ratio of the fugacity of the component at actual conditions over the fugacity of the component at standard conditions. (8)

$$a_i(T,P,x) = f_i(T,P,x) / f_i(T,P^o,x^o)$$

where $a_i$ – component activity
T – temperature at actual conditions
P – pressure at actual conditions
x – liquid mole fraction at actual conditions.
Note: The superscript "o" indicates at standard state.

The liquid activity models are designed to have more flexibility by having more adjustable parameters and allow the free energy curve to be accurately tuned for magnitude and skewness. One of the key features of these models is treating liquids differently than vapors. The liquids are evaluated as deviations from ideal-solution behavior, where as the vapors are evaluated as deviations from ideal-gas behavior. (8)

One of the best thermodynamic models to use when designing wastewater strippers is the NRTL equation. (6)

The NRTL (Non-Random Two Liquid) equation is a three-parameter equation that can be used for both liquid-liquid and vapor-liquid equilibria correlations. The strength of the NRTL equation is for highly non-ideal systems. The NRTL equation often provides a good representation of highly non-ideal mixtures, polar compounds and partially immiscible systems. The NRTL equation provides good representation of experimental data if care is exercised in data reduction to obtain the adjustable parameters in the equation. (8)

**Design Curve:**

In order to determine the accuracy of a simulation it is always desirable to construct a design diagram similar to a McCable-Thiele diagram from the data generated from the simulation. The data from the simulation can be easily transferred to a software package where the graph can be constructed. This graph is used more as a tool to identify possible problems that won't be discovered until the column fails. The following is a list of the areas where a design diagram can be used as a powerful analysis tool (8).

1. Pinched regions - Pinching is readily seen on an x-y diagram.

2. Insufficient Stages Specified – Once the equilibrium curve and operating curve has been constructed the total number of stages can be determined.

3. Determining the minimum liquid to gas ratio to be used for the design. The actual design value of $L_s/G_s$ normally should be around 20 to 50 percent higher than the minimum, so the actual design operating line will intersect the line $x = x_2$ at a point somewhat below the equilibrium line.

**Column Diameter and Pressure Drop:**

Flooding determines the minimum possible diameter of the stripping column, and the usual design for flood is for 60 to 80 percent. Pressure drop in strippers should be minimized as much as possible.

Some wastewater systems have a propensity for fouling in the form of foaming. In many systems an operating froth can be observed on the liquid phase. In distillation systems, the decrease in surface tension as equilibrium temperature rises promotes foaming. High gas velocities (Such as Steam Injection) allow liquid to be entrained into the vapor phase. In non-foaming systems liquid disengagement from the vapor stream is relatively easy. Foaming makes liquid disengagement from vapor flow difficult. When foaming becomes severe it can lead to a reduction in capacity and loss of efficiency. To counter this effect stripping columns that operate in foaming systems are run a lower vapor and liquid rates to reduce the amount of froth generated. Sometimes anti-foam additives are added to stripping columns to decrease the amount of foam generated in the column. There are drawbacks to using anti-foam chemicals. Sometimes they may contaminate the end product and produce product that does not meet production specifications. (4)

**Calculation of Tower Height**

The required height of a steam stripper column depends on the following:

1. The phase Equilibrium
2. The specified level of material to be removed from the liquid stream to the gas stream.
3. The mass-transfer efficiency of the trays or packing installed.

These same considerations apply both to tray towers and packed towers. Items 1 and 2 dictate the required number of theoretical stages (tray tower) or transfer units (packed tower). Item 3 is derived from the tray efficiency and spacing (tray tower) or from the height of one transfer unit (packed tower). Solute-removal specifications normally are specified in the early part of the design phase.

**Tray Efficiencies in Tray Strippers:**

Computations of the number of theoretical stages $N_{Theoretical}$ assume that the liquid on each plate is completely mixed and that the vapor leaving the plate is in equilibrium with the liquid. The condition of complete equilibrium cannot exist since interphase mass transfer requires a finite driving-force difference. This leads to the definition of an overall tray efficiency, which is defined by the following equations.

$N_{Theoretical}=\ln((1-1/S)(x_{in}/x_{out}))/((x_{in}/x_{out})+1/S)/\ln(S)$ (1)

S – Stripping Factor ($mG_m/L_m$)
m – Equilibrium Curve Slope
$G_m$ – Gas Phase Flow, lbmol/hr

$L_m$ – Liquid Phase Flow, lbmol/hr

$N_{Actual}$=Total Number Of Actual Trays

%-Efficiency = (Number of Theoretical Stages/Number Of Actual Trays)*100
$E= N_{Theoretical}/ N_{Actual}$
Tray efficiency in wastewater strippers is most likely to be affected by the physical properties of the fluid in the tower and the dimensionless ratio, The Stripping Factor, $mG_s/L_s$. Trays in wastewater strippers usually have tray efficiencies around 25 to 40 percent. This range of efficiency has been confirmed by independent testing. The efficiency of trays depends heavily of the physical properties of the feed liquid (Salts, Polymer, etc. affect tray efficiency). (6)

**Packed Towers:**

In order to calculate the overall height of packing required for a tower design you must first calculate the number of transfer units in the liquid phase.

$NTU_L$=(S/S-1)*ln((1-1/S)($x_{in}/x_{out}$)+1/S) (2)

$HTU_L$=Height Of Liquid Transfer Unit for packing (Usually Provided By The Vendor)

$Z= NTU_L * HTU_L$

NTU – The Number Of Liquid Transfer Units
S – Stripping Factor ($mG_m/L_m$)
m – Equilibrium Curve Slope
$G_m$ – Gas Phase Flow, lbmol/hr
$L_m$ – Liquid Phase Flow, lbmol/hr
$HTU_L$=Height of Overall Transfer Unit, inches
Z=Height of Packing, inches

In recent years packed wastewater stripper towers have become very popular. Random packing is the packing of choice for this type of service. Structure packing is more efficient than random packing but is extremely susceptible to fouling. However, there are a few things to remember when trying to decide if packing is correct for your application. The vapor and liquid loadings of the tower are important when considering packing. Generally this type of column involves very high liquid loads and low vapor loads.

Some other items to consider when deciding to use packing in a wastewater stripper are as follows:

1. Is your application a fouling service? Usually certain types of packings do not perform well in heavy fouling applications.

2. Is your service highly corrosive? Some types of packing are not good in a highly corrosive service.

3. Is pressure drop a major consideration? Random packing is a low-pressure drop device that provides good efficiency. High pressure drop in atmospheric and vacuum stripping columns can effect the performance of the column. This is done by affecting the temperature in the bottom of the column.

4. Does the system your modeling have foaming tendencies? (5).

The most important part of a packed tower design is the distributors. Packed towers are more sensitive to liquid and vapor maldistribution than trayed towers. Therefore, it is critical that vapor and liquid enter packing evenly distributed. The performance of the packing depends heavily on the initial vapor and liquid distribution entering the packing. Poor vapor and liquid distribution to a packed bed can result in a loss of efficiency (7).

**Tray Towers:**

Trays are the most commonly selected type of tower internal. Just like packed towers; vapor and liquid loadings are an important consideration for trayed towers. Generally trays perform well at high liquid and vapor loadings. At low flow parameters the capacity and efficiency of trays can be reduced.

Below are some other items to consider when deciding to use trays in a tower.

1. Is your application a fouling service? Usually trays have downcomer capacity problems in heavy foaming services.

2. Is your service highly corrosive? Trays have a high resistance to corrosion if the correct material is selected.

3. Trays have higher pressure drop than random packing does.

4. Entrainment is an issue with trays. Trays usually have more entrainment than packings. Excessive entrainment can lead to efficiency loss.

5. Excessive vapor and liquid maldistribution can lead to a loss of efficiency in a tray tower.

When comparing trays to packing it is always a good idea to get as much information as possible about the internals being considered. The tray vendors are a good source of information. There are many publications on the subject of distillation for example “Distillation Design” by Henry Kister (7). Talk with others in the industry to see what has been done before. Do as much research as possible before any decisions are made.

**Design Example:**

**Table 1** gives the feed stream design basis that was used in the wastewater stripper example presented in this paper.

**TABLE 1**

| Design Parameter | Parameter |
|---|---|
| Feed Rate (LB/Hr) | 90,000 |
| Feed Temperature (°F) | 250 |
| Feed Inlet Pressure (Psia) | 92.0 |
| Inlet Water Mass Fraction | 0.9949211 |
| Inlet Dissolved Hydrocarbon Mass Fraction | 6.289e-4 |
| Inlet Inorganic Solute Mass Fraction | 4.45e-3 |

The operating parameters of the column are given below in **Table 2**.

**TABLE 2**

| Design Parameter | Parameter Range |
|---|---|
| Steam Feed Rate (LB/Hr) | 3,000 |
| Operating Temperature (°F) | 245 - 250 |
| Operating Pressure (Psig) | 28 - 30 |
| Outlet Water Mass Fraction | 0.999067 |
| Outlet Dissolved Hydrocarbon Mass Fraction | 4.1623e-7 |
| Outlet Inorganic Solute Mass Fraction | 9.31e-4 |

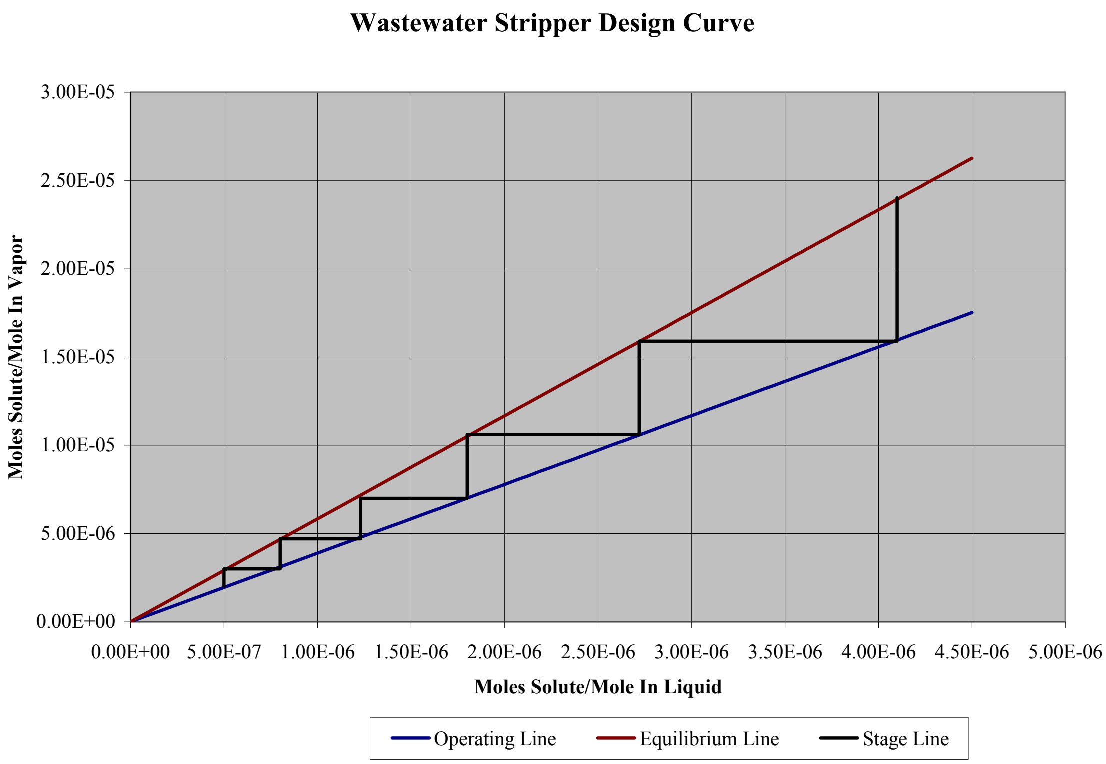
Based on the feed composition and the operating parameters of the column a design simulation was generated. The results of the simulation are shown in **Table 3**.

**Simulation Results**

**TABLE 3**

| Design Parameter | Parameter |
|---|---|
| Total Number Of Stages | 5 |
| Overall Tray Efficiency (Calculated) | 25.0% |
| Thermodynamic Model Used | NRTL |
| Calculated Stripping Factor | 5.84 |
| Total Number Of Actual Trays | 20 |

Based on the above design information a design curve for this column was generated.




In stripping columns the equilibrium curve is always above the operating line.

**Conclusions:**

1. It is very importance that when designing a steam stripper that the designer has a complete understanding of the chemistry of the feed stream.

2. Typically the best type of thermodynamic equation to use for steam strippers is one that uses activity coefficients that can predict immiscibility (Non-Ideal Conditions).

3. The operating pressure of a steam stripper can influence the efficiency and reliability of the column.

4. Trays in wastewater strippers usually have tray efficiencies around 25 to 40 percent.

5. Preheating the feed before it is introduce into the column is important because it reduces the amount of heat added to the column to achieve the desired separation.

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