

“Resolving Process Distillation Equipment Problems”

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Introduction

In most chemical processing systems two main unit operations dominate; chemical reaction followed by separation. The chemical reaction step is normally completed in a reactor. The reactor can be in numerous forms, from a plug flow reactor, to a CSTR (Continuously Stirred Tank Reactor), which can be in the form of a batch reactor, to a fixed or a fluidized catalytic bed reactor. From the reactor the reactants are then sent to a separation unit. The reactants are separated into desired products, unreacted products for recycle, and unwanted or by products.

Most Separation Units contain distillation equipment. Distillation Equipment was developed to separate ethanol from the by-products of fermentation. From the original batch stills, distillation equipment has progress to the type of trayed and packed columns used today. Today columns range from absorbers, extractors, strippers, and rectifying towers. They include vapor / liquid columns, liquid / liquid columns, and extractive distillation and reactive distillation columns. Vapor / liquid columns are designed to separate products by boiling point differences. Liquid / Liquid columns are designed to separate products by a physical property difference such as polarity. Extractive and reactive distillation columns shift equilibrium by removing one of the products to improve the equilibrium distribution.

General Distillation Equipment Design

The first step in resolving any distillation problem is to understand the operating and technical fundamentals of the column. Knowledge of how a column functions, hydraulic constraints, thermodynamic and equilibrium limits, and heat and material balances are required. This knowledge needs to be accumulated in advance of formulating any resolution of a problem.

At least three types of distillation equipment problems exist. The first problem is inappropriate design, the second problem is inappropriate operation, and the third is potential damage to internal equipment. Before a process is shut down for repairs the inappropriate design and damage to internal equipment should be determined, and inappropriate operation should be eliminated.

Appropriate Stage Design

The design of stage operations has progressed from a trial and error basis to a computer-modeled system. The computer-modeled system can become an error-based system if operational feedback is not utilized. The computer model should match existing field data if the tower is operating properly, and if not, field data should be re-verified. If field data is accurate, the model should be adjusted to match existing data. The computer model can be verified by developing a McCabe-Thiele plot to verify the number of separation stages required. If you assume that the model is correct in all cases, you will soon have opportunities for new employment.

Trayed Columns utilize a pressure and temperature differential, to create a mass transfer gradient, to separate the products. Packed Columns generate a mass transfer area by providing a large surface area over which the liquid can transfer heat and mass to the vapor.

Pressure is a very important constraint in stage design. In low-pressure systems the vapor is considered the continuous phase and in high-pressure systems the liquid is considered the continuous phase. In low-pressure systems packing can be successfully utilized. In high-pressure systems packing can fail, due to a back mixing mechanism, therefore trays are the preferred system.

The temperature at which the reflux can be condensed usually determines the tower pressure. Normally the preferred temperature is that of cooling water. If cooling water cannot be used, the pressure is set using the best combination of variables. The first variable is that hydrocarbons separate easier at lower pressures, because the differences in their relative volatilities are larger at lower pressures. Therefore lower pressure equates to less reflux, less stages and smaller columns.

The second variable is the increased cost of cooling at lower pressures. Often at lower pressure, refrigeration is needed equating to increased operating cost. A balance has to be constructed between capital cost and operating cost. This balance is also utilized in the determination of the amount of reflux versus the number of stages. This balance is between the energy requirement versus the cost of the additional stages. Computer based models have made this balance optimal.

Minimum Reflux Ratio and Minimum Number of Stages by use of Simulation

To determine the minimum reflux ratio and the minimum number of stages, one develops a reflux-stage plot and extrapolates from it. To develop this plot, simulation runs are performed at different number of stages while keeping the material balance, product compositions, and the ratio of the feed stage to the number of stages constant. The reflux ratio is allowed to vary. Then a plot of the number of stages versus reflux or reflux ratio is plotted. The curve is extrapolated asymptotically to an infinite number of stages to obtain the minimum reflux ratio and asymptotically to an infinite reflux ratio to obtain the minimum number of stages

Optimization of Feed Stage by Simulation

To determine the optimum feed stage, simulation runs can be performed at several different feed positions. In the simulation runs, the material balance, reflux ratio, and total number of stages need to be kept constant. Then two main plots can be created. One plot is the McCabe-Thiele diagram and the other is a concentration versus feed stage diagram. The McCabe-Thiele diagram is plotted using the mole fraction data calculated for each stage by the simulation. The equilibrium data and the operating lines are determined from this data. The McCabe-Thiele diagram then shows how an optimum feed stage versus a non-optimum feed stage looks when using the simulation data.

Pressure Choices

Many times when designing a distillation tower, the controlling factor in choosing the column pressure is the heating requirements of the reboiler or the condensing requirements of the overhead condenser. For example, a new column was being installed to separate benzene and toluene. For this design case the controlling factor in choosing the column pressure was the ability to use low-pressure boiler feed water as a condensation medium to produce low-pressure steam. This choice would mean that the column was going to operate under pressure. Performing this separation under pressure had a couple of advantages.

1. Increasing the column pressure would increase the vapor density and therefore the vapor handling capacity. This would lead to a reduction in the diameter of the column, which would reduce the overall cost of the project.
2. It would allow the possibility of having the benzene-toluene splitter share a condenser with a tower used to remove benzene from vent gas. Both columns' overhead products would go to the same location. The cost of installing a complete condenser system for this column would be considerably reduced.

However, in raising the column's operating pressure there are some unfavorable effects.

1. Raising the pressure lowers the relative volatility and increases the separation difficulty.
2. Raising the pressure also raises the reboiler temperature, thereby requiring a more expensive heating medium. A reboiler with a larger heat transfer area would be required.
3. Above 100 psig pressure, the columns shell thickness increases in order to handle the higher pressures. This will constitute an increase in capital costs.

Reboiler Design and Selection

Several types of reboilers can be selected based upon operational needs and reboiler duty requirements. For larger duty requirements forced circulating reboilers are required. The lowest in cost are the once through thermosyphon reboilers and they are preferred if the required duty can be delivered. If fouling due to low velocities or a higher duty is required a circulating thermosyphon reboilers or forced circulation reboilers may be preferred.

Most types of reboilers use condensing steam as a heating medium. Steam condensation may occur on the shell side or the tube side depending of the type of reboiler used. The steam flow may be horizontal or vertical. As with all condensing systems, it is very important to see that the system is regularly vented to prevent the build up of non-condensable gas in the system. Non-condensable gas in condensers is the most common reason why the condensation heat transfer coefficient is less than expected.

In industry many different types of reboilers are used. Overviews of three types used are given below.

1 Vertical Thermosyphon Reboiler

A vertical thermosyphon reboiler is very similar to a long tube evaporator and a climbing film evaporator. Liquid from the column sump flows through the inlet leg of the reboiler, enters the bottom channel, and is distributed uniformly to the tubes. A shell-side fluid, often condensing steam heats the tubes. Condensate flow in this type of reboiler is vertical. The process fluid entering the tubes is below its boiling point due to static head effects and must undergo sensible heating; for vacuum systems, such heating may consume a significant portion of the tube length.

Heat is transferred by both nucleate boiling and two-phase convective mechanisms. The two-phase mixture exiting from the heated zone returns to the column for disengagement of the phases, with the net vapor representing the needed boil-up for the distillation process and the liquid representing a recycle. Good design calls for vaporization per pass in the range of 10% to 30%; thus, there is a significant recycle flow.

The advantages of the vertical thermosyphon reboiler are the low residence time of the process liquid, the low liquid inventory of process fluid and, the low floor area required. Another advantage of this type of reboiler is the high heat transfer coefficients that are obtained. Vertical thermosyphon reboilers are usually the best value for the heat supplied. This type of reboiler can be used in fouling services because these exchangers are easy to clean.

The disadvantage of this type of exchanger is that they require extensive amounts of headroom. A distillation column may have to be raised off the ground in order to accommodate the reboiler. This may cause a mechanical design problem with the column. Stability of the column may become an issue.

2 Horizontal Thermosyphon Reboiler

This is perhaps the most common type of reboiler. A horizontal thermosyphon reboiler consists of a horizontal shell and tube exchanger with a single horizontal baffle. The process fluid flows along the shell-side along the length of the tube bundle from its point of entry midway along the shell to the ends. The fluid then turns 180° and flows back to the midpoint of the shell along the upper part of the shell. Boiling takes place over most of this flow path. The heating medium, usually steam, flows inside the tubes usually in two paths. The steam enters along the upper pass and leaves along the lower pass, allowing the condensate to drain naturally out of the bundle. The flow of process fluid through the reboiler is governed by thermosyphon action, although a pump could be installed in the inlet pipe if necessary. The flow rate through this type of reboiler is controlled by density differences.

The main advantage of the horizontal thermosyphon reboiler is the ease of removing the tube bundle for cleaning. Also, the horizontal arrangement permits a lower elevation of the return line. This allows for a lower column elevation in relation to the reboiler elevation.

3 Kettle Type Reboiler

The kettle reboiler is similar to a shell-side evaporator. The heating fluid is usually condensing steam flows inside the tubes, which are commonly U-Tubes. The U-Tube bundle occupies the lower part of the K-Type shell. Liquid boiling is outside the tubes and the eccentric bundle arrangement makes available space for vapor-liquid disengagement. An internal weir controls the liquid level in the shell. The liquid level is such that the top of the bundle is only just submerged. The liquid enters the reboiler by gravity feed. A valve usually controls the feed. The overflow from the weir is the bottom product of the distillation column. If necessary a pump can be installed in the pipe between the distillation column and the reboiler. A properly designed kettle can produce a near-equilibrium vapor mixture and thus can provide an extra theoretical stage for the separation. It has an advantage of convenient bundle removal for tube inspection, and is relatively insensitive to varying loads of vapor production. It is comparatively expensive, however due to the type of shell design used for this type of reboiler.

Trayed Columns Design

One of the very first trays to be developed was the sieve tray. It is essentially a plate with holes punched into the plate. The number and size of the holes is based on the vapor flow up the tower. The liquid flow is transported down the tower by downcomers, a dam and overflow device on the side of the plate, which maintains a set liquid level on the tray. To maintain the liquid level on the tray a minimum amount of vapor traffic up the tower must be maintained, or the liquid level on the tray will weep down to the next tray through the holes punched on the plate. Typically sieve deck trays have a minimum capacity, or downturn, of approximately 70%.

One of the next developments was to add a variable valve opening to the tray deck. This valve would open in relation to the vapor flow. The advantage to this design was the ability to maintain the liquid level on the tray deck. Typically valve deck trays have a minimum capacity, or downturn, of approximately 60%.

Some of the latest developments in tray design include changes to the downcomer and changes in the valve design. The downcomer requires a disengaging area to separate the liquid from the vapor. This area requires a minimum distance that normally sets the tray spacing. To use multiple downcomers reduces this distance and the total height of the tower. The liquid is required to travel across the deck to the next downcomer. If the valves are designed to help direct the liquid flow across the deck, by directing the vapor, the total time on the deck will be reduced leading to increased capacity. Trays are the most commonly selected type of tower internal. Generally trays perform well at high liquid and vapor loadings. At low flow parameters the capacity and efficiency of trays can be reduced.

Some other items to consider when deciding to use trays in a tower.

1. Trays have downcomer capacity problems in heavy foaming services.
2. Trays have a high resistance to corrosion.
3. Trays have higher pressure drop than structured packing or random packing.
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 mal-distribution can lead to a loss of efficiency in a tray tower.

Mal-distribution can be caused by the feed and reflux inlet design. A good feed and reflux design will affect the equilibrium on the feed tray and the adjacent trays slightly. A poor inlet design can affect several trays above and below the feed point. If a tower has 20 trays and a poor inlet feed design disrupts the equilibrium on 4 of the trays, the capacity and efficiency of the tower can be reduced by 20%. Installing better inlet designs is an efficient way to improve separation.