Distillation

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an introduction

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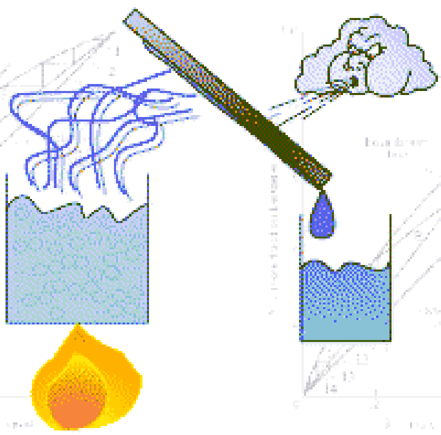
Distillation is defined as:

a process in which a liquid or vapour mixture of two or more substances is separated into its component fractions of desired purity, by the application and removal of heat.



Distillation is based on the fact that the vapour of a boiling mixture will be richer in the components that have lower boiling points.

Therefore, when this vapour is cooled and condensed, the condensate will contain more volatile components. At the same time, the original mixture will contain more of the less volatile material.

Distillation columns are designed to achieve this separation efficiently.

Although many people have a fair idea what “distillation” means, the important aspects that seem to be missed from the manufacturing point of view are that:

- distillation is the most common separation technique
- it consumes enormous amounts of energy, both in terms of cooling and heating requirements
- it can contribute to more than 50% of plant operating costs

The best way to reduce operating costs of existing units, is to improve their efficiency and operation via process optimisation and control. To achieve this improvement, a thorough understanding of distillation principles and how distillation systems are designed is essential.

The purpose of this set of notes is to expose you to the terminology used in distillation practice and to give a very basic introduction to:

- types of columns
- basic distillation equipment and operation
- column internals
- reboilers
- distillation principles
- vapour liquid equilibria

- distillation column design and
- the factors that affect distillation column operation

TYPES OF DISTILLATION COLUMNS

There are many types of distillation columns, each designed to perform specific types of separations, and each design differs in terms of complexity.

Batch and Continuous Columns

One way of classifying distillation column type is to look at how they are operated. Thus we have:

- batch and
- continuous columns.

Batch Columns

In batch operation, the feed to the column is introduced batch-wise. That is, the column is charged with a 'batch' and then the distillation process is carried out. When the desired task is achieved, a next batch of feed is introduced.

Continuous Columns

In contrast, continuous columns process a continuous feed stream. No interruptions occur unless there is a problem with the column or surrounding process units. They are capable of handling high throughputs and are the most common of the two types. We shall concentrate only on this class of columns.

Types of Continuous Columns

Continuous columns can be further classified according to:

the nature of the feed that they are processing,

- binary column - feed contains only two components
- multi-component column - feed contains more than two components

the number of product streams they have

- multi-product column - column has more than two product streams

where the extra feed exits when it is used to help with the separation,

- extractive distillation - where the extra feed appears in the bottom product stream
- azeotropic distillation - where the extra feed appears at the top product stream

the type of column internals

- **tray** column - where trays of various designs are used to hold up the liquid to provide better contact between vapour and liquid, hence better separation
- **packed** column - where instead of trays, 'packings' are used to enhance contact between vapour and liquid

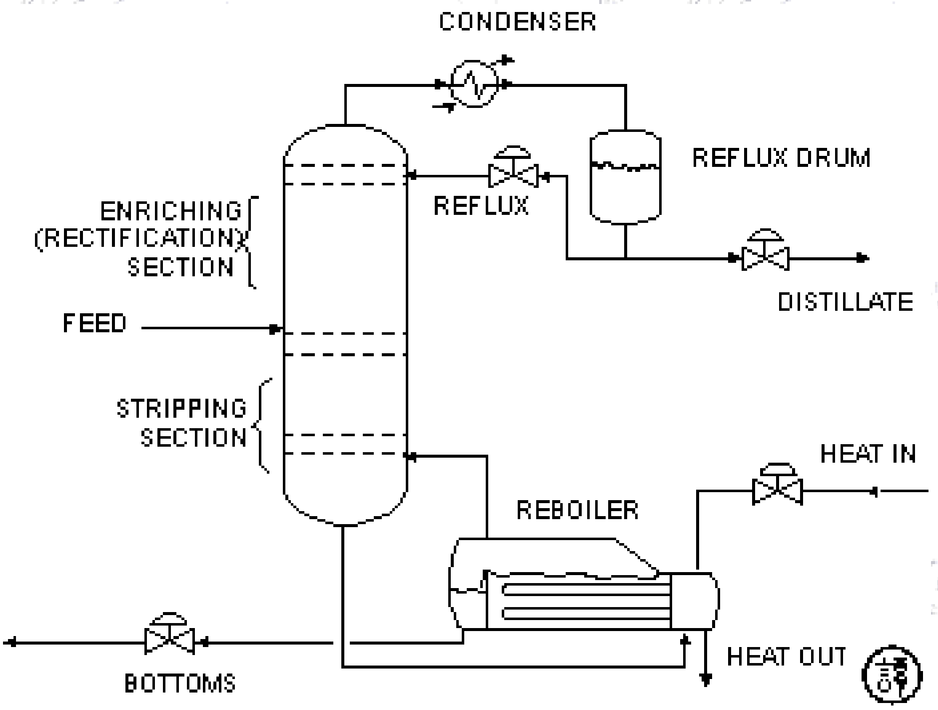
BASIC DISTILLATION EQUIPMENT AND OPERATION

Main Components of Distillation Columns

Distillation columns are made up of several components, each of which is used either to tranfer heat energy or enhance materail transfer. A typical distillation contains several major components:

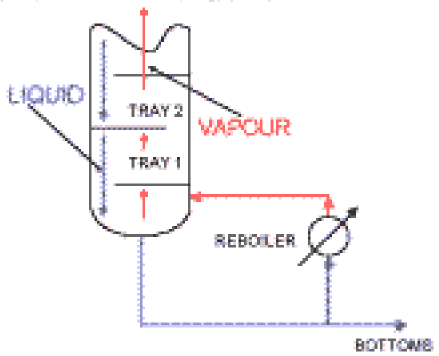
- a vertical shell where the separation of liquid components is carried out
- column internals such as trays/plates and/or packings which are used to enhance component separations
- a reboiler to provide the necessary vaporisation for the distillation process
- a condenser to cool and condense the vapour leaving the top of the column
- a reflux drum to hold the condensed vapour from the top of the column so that liquid (reflux) can be recycled back to the column

The vertical shell houses the column internals and together with the condenser and reboiler, constitute a distillation column. A schematic of a typical distillation unit with a single feed and two product streams is shown below:



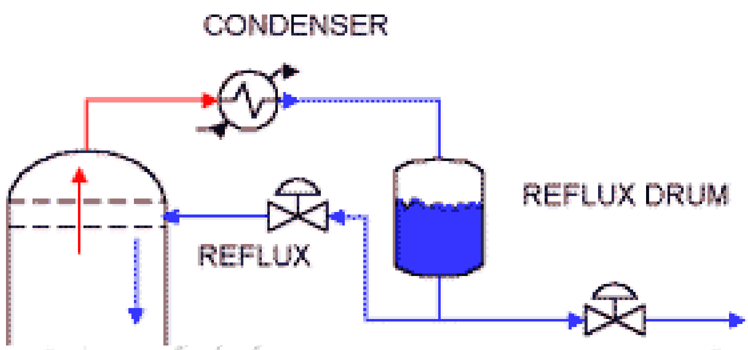
Basic Operation and Terminology

The liquid mixture that is to be processed is known as the feed and this is introduced usually somewhere near the middle of the column to a tray known as the feed tray. The feed tray divides the column into a top (enriching or rectification) section and a bottom (stripping) section. The feed flows down the column where it is collected at the bottom in the reboiler.



Heat is supplied to the reboiler to generate vapour. The source of heat input can be any suitable fluid, although in most chemical plants this is normally steam. In refineries, the heating source may be the output streams of other columns. The vapour raised in the reboiler is re-introduced into the unit at the bottom of the column. The liquid removed from the reboiler is known as the bottoms product or simply, bottoms.

The vapour moves up the column, and as it exits the top of the unit, it is cooled by a condenser. The condensed liquid is stored in a holding vessel known as the reflux drum. Some of this liquid is recycled back to the top of the column and this is called the reflux. The condensed liquid that is removed from the system is known as the distillate or top product.



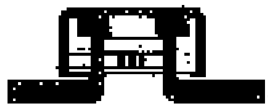
Thus, there are internal flows of vapour and liquid within the column as well as external flows of feeds and product streams, into and out of the column.

COLUMN INTERNALS

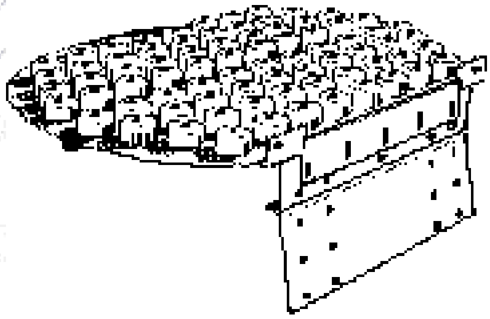
Trays and Plates

The terms "trays" and "plates" are used interchangeably. There are many types of tray designs, but the most common ones are :

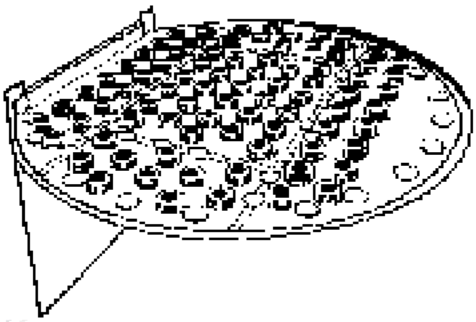
Bubble cap trays



A bubble cap tray has riser or chimney fitted over each hole, and a cap that covers the riser. The cap is mounted so that there is a space between riser and cap to allow the passage of vapour. Vapour rises through the chimney and is directed downward by the cap, finally discharging through slots in the cap, and finally bubbling through the liquid on the tray.



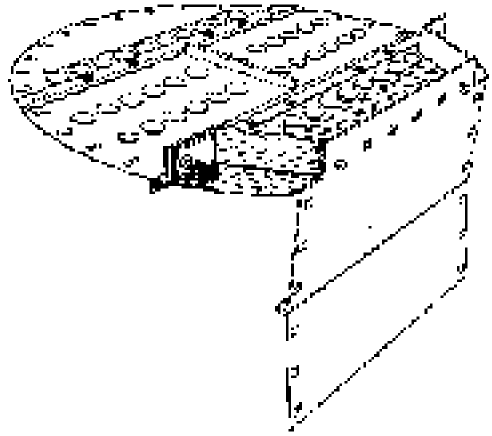
Valve trays



In valve trays, perforations are covered by liftable caps. Vapour flows lifts the caps, thus self creating a flow area for the passage of vapour. The lifting cap directs the vapour to flow horizontally into the liquid, thus providing better mixing than is possible in sieve trays.

Valve trays (photos courtesy of Paul Phillips)

Sieve trays

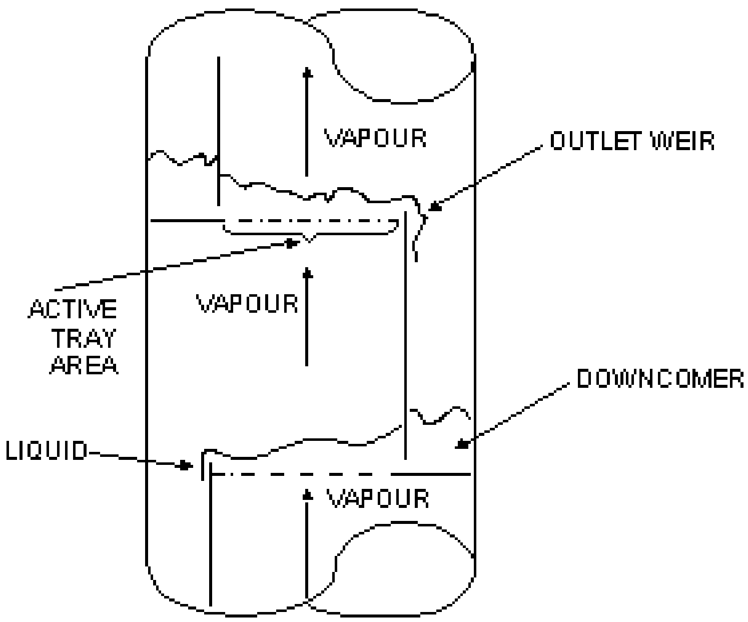


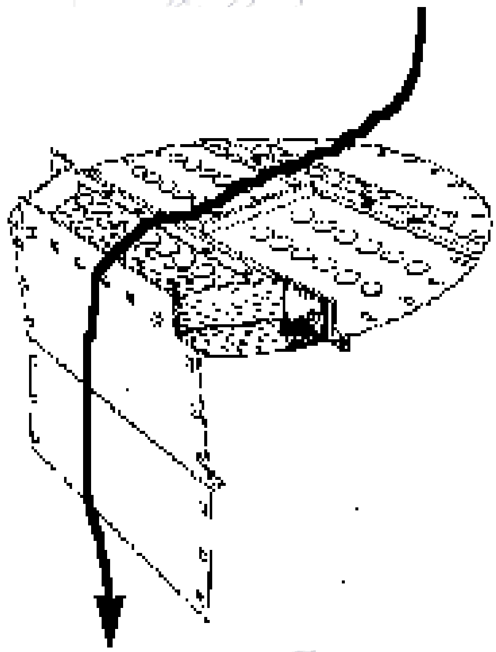
Sieve trays are simply metal plates with holes in them. Vapour passes straight upward through the liquid on the plate. The arrangement, number and size of the holes are design parameters.

Because of their efficiency, wide operating range, ease of maintenance and cost factors, sieve and valve trays have replaced the once highly thought of bubble cap trays in many applications.

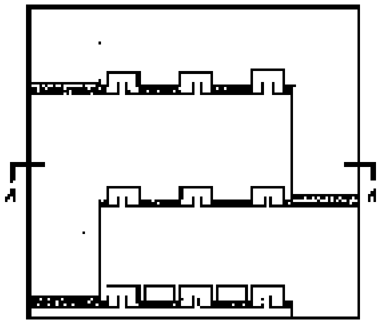
Liquid and Vapour Flows in a Tray Column

The next few figures show the direction of vapour and liquid flow across a tray, and across a column.



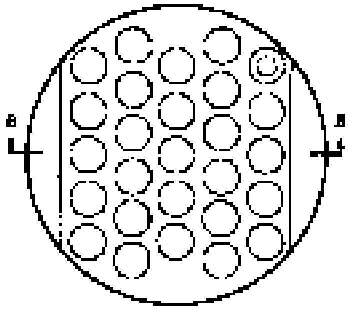


Each tray has 2 conduits, one on each side, called ‘downcomers’. Liquid falls through the downcomers by gravity from one tray to the one below it. The flow across each plate is shown in the above diagram on the right.



A weir on the tray ensures that there is always some liquid (holdup) on the tray and is designed such that the the holdup is at a suitable height, e.g. such that the bubble caps are covered by liquid.

Being lighter, vapour flows up the column and is forced to pass through the liquid, via the openings on each tray. The area allowed for the passage of vapour on each tray is called the active tray area.



The picture on the left is a photograph of a section of a pilot scale column equiped with bubble capped trays. The tops of the 4 bubble caps on the tray can just be seen. The down- comer in this case is a pipe, and is shown on the right. The frothing of the liquid on the active tray area is due to both passage of vapour from the tray below as well as boiling.

As the hotter vapour passes through the liquid on the tray above, it transfers heat to the liquid. In doing so, some of the vapour condenses adding to the liquid on the tray. The condensate, however, is richer in the less volatile components than is in the vapour. Additionally, because of the heat input from the vapour, the liquid on the tray boils, generating more vapour. This vapour, which moves up to the next tray in the column, is richer in the more volatile components. This continuous contacting between vapour and liquid occurs on each tray in the column and brings about the separation between low boiling point components and those with higher boiling points.

Tray Designs

A tray essentially acts as a mini-column, each accomplishing a fraction of the separation task. From this we can deduce that the more trays there are, the better the degree of separation and that overall separation efficiency will depend significantly on the design of the tray. Trays are designed to maximise vapour-liquid contact by considering the

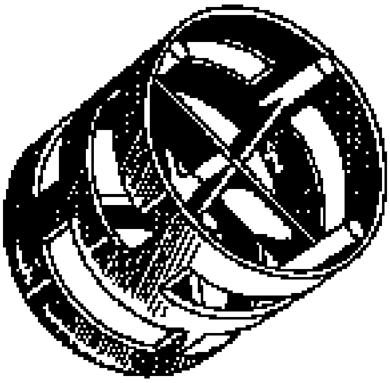
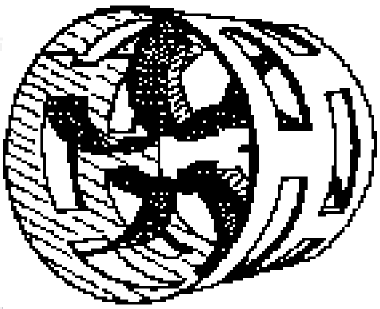
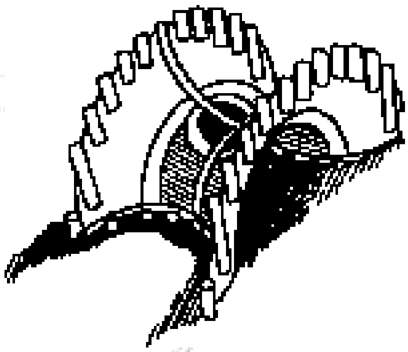
- liquid distribution and
- vapour distribution

on the tray. This is because better vapour-liquid contact means better separation at each tray, translating to better column performance. Less trays will be required to achieve the same degree of separation. Attendant benefits include less energy usage and lower construction costs.

Liquid distributors - Gravity (left), Spray (right)
(photos courtesy of Paul Phillips)

Packings

There is a clear trend to improve separations by supplementing the use of trays by additions of packings. Packings are passive devices that are designed to increase the interfacial area for vapour-liquid contact. The following pictures show 3 different types of packings.

These strangely shaped pieces are supposed to impart good vapour-liquid contact when a particular type is placed together in numbers, without causing excessive pressure-drop across a packed section. This is important because a high pressure drop would mean that more energy is required to drive the vapour up the distillation column.

Structured packing (photo courtesy of Paul Phillips)

Packings versus Trays

A tray column that is facing throughput problems may be de-bottlenecked by replacing a section of trays with packings. This is because:

- packings provide extra inter-facial area for liquid-vapour contact
- efficiency of separation is increased for the same column height
- packed columns are shorter than trayed columns

Packed columns are called continuous-contact columns while trayed columns are called staged-contact columns because of the manner in which vapour and liquid are contacted.

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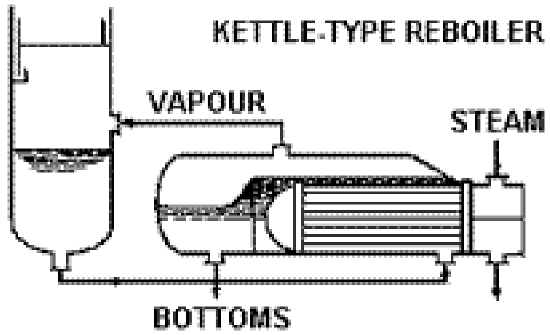
This technology applies the circulation of solid particles through the tubes to remove fouling deposits from the tube wall.

COLUMN REBOILERS

There are a number of designs of reboilers. It is beyond the scope of this set of introductory notes to delve into their design principles. However, they can be regarded as heat-exchangers that are required to transfer enough energy to bring the liquid at the bottom of the column to boiling boint. The following are examples of typical reboiler types.



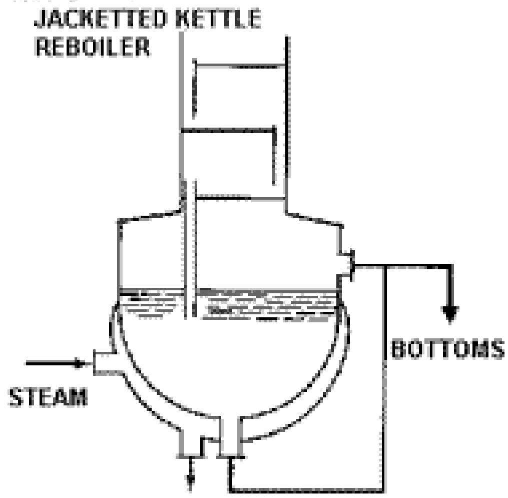
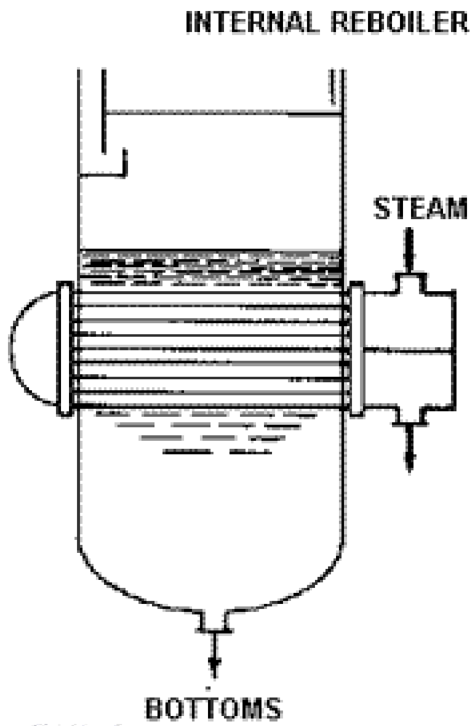
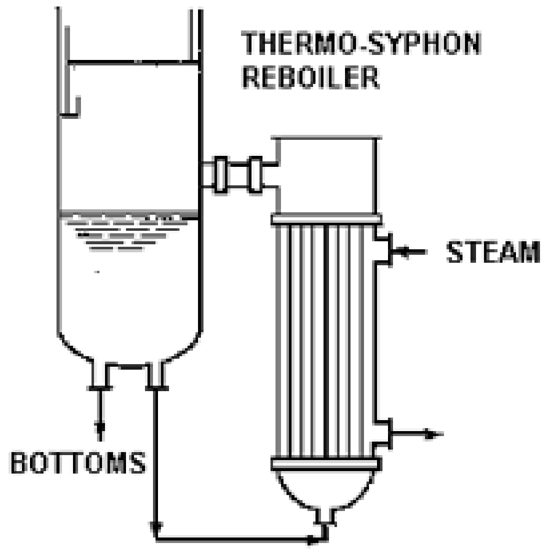


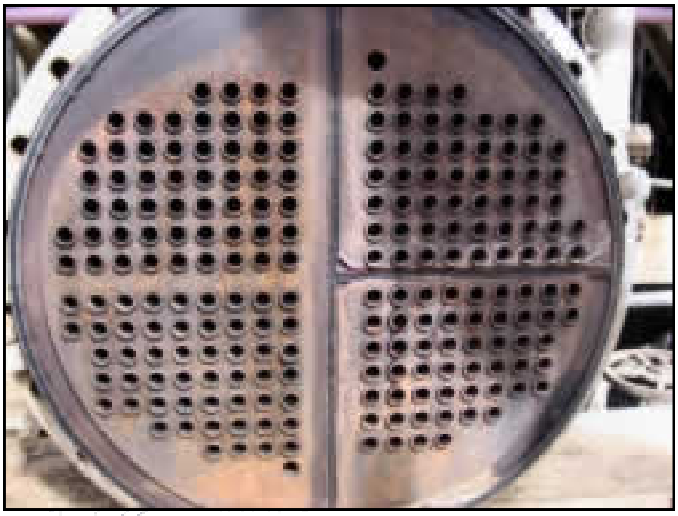
Photo courtesy of Brian Kennedy





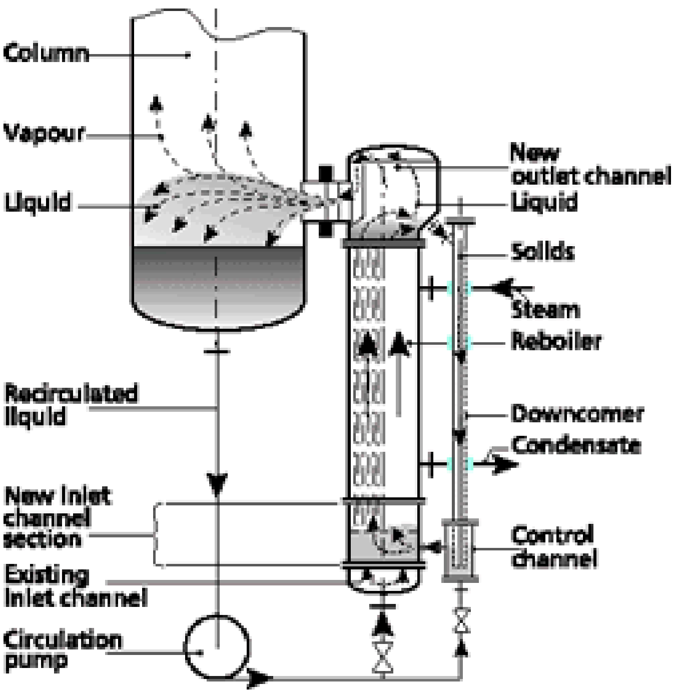
Tube bundle
(photo courtesy of Paul Phillips)

Tube bundle
(photo courtesy of Paul Phillips)



Tubesheet
(photo courtesy of Paul Phillips)

Fitting a Shell & Tube Heat Exchanger
(photo courtesy of Paul Phillips)



A novel development in reboiler design is the self-cleaning shell-and-tube heat exchangers by Klarex Technology for applications where heat exchange surfaces are prone to fouling by the process fluid. Particles are introduced into the process stream and these produce a scouring action on the heat exchange surfaces. An example is shown in the diagram on the left. [Click on it to find out more]