FLOW PHENOMENA IN STAGED AND NON STAGED DISTILLATION EQUIPMENT

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ABSTRACT

In Staged and Non Staged Distillation Equipment, there can be two types of liquid flow that may either assist or impede heat and mass transfer; a macro and micro flow phenomena. The macro flow phenomena deals with the mixing of the continuous liquid phase in large divisions of the column. If inferior mixing is present, this can lead to differing concentrations of the heavy and light keys within the column even on the same stage.

The micro flow phenomenon is based on the point flow, the liquid stream not fully mixed in small sections of the column leading to loss in stage efficiency. In non-staged equipment the down coming liquid can coalesce into larger flow streams, reducing the mass transfer with the rising vapor. In staged equipment, the eddy diffusion on an individual tray can lead to inactive zones where no separation occurs.

Two case studies will be presented which deal with inferior macro and micro flow phenomena. An inferior macro / micro phenomenon cannot be detected by utilizing McCabe-Thiele or simulation software in the conceptual stages. The macro / micro flow phenomena must be reviewed in the mechanical drawing review stage to eliminate the possibility.

Keywords: Flow phenomena, distillation equipment.

1. INTRODUCTION

Distillation is one of the older means of separation that has been used in large-scale chemical industries. Tall and magnificent distillation columns became a symbol that chemical engineers relate their career. Despite many textbooks and technical papers were written on distillation in the last half century, the kinetic and flow phenomena inside the column is still not well understood by many quarters of students, technicians and even practising engineers in the industries.

Students of unit operations are taught phase equilibria and how a distillation system can be designed using simple graphical technique like McCabe-Thiele principle. However, there is little or no discussion on the complex flow pattern and transport phenomena driving the separation in the distillation equipment. To a plant operator, a distillation column is operated by maintaining a certain temperature profile and controlling the reflux ratio to achieve the product purity. Very often, they do not posses the knowledge on how to extend the operating window through better understanding of the flow phenomena of different distillation equipment.

This paper is aimed at this subset of the chemical engineering fraternity and relates flow phenomena to the knowledge of common distillation principles they already posses. When the knowledge of the two fields is coupled, a chemical engineer, both in design and operations function, can greatly improve new or existing distillation equipment.

2. TYPES OF DISTILLATION EQUIPMENT

2.1. Background

The first application of distillation, as in separation of spirits from water using stills is based on the concept of equilibrium. Each still is able to reach a state of equilibrium and effectively, a single stage of separation. Such unit operation is entirely controlled as a function of time, as many of the early applications were carried out batch-wise. Flow phenomena are not considered since the separation will not be kinetic controlled.

When tray and packed columns began in use, the separation achieved was poor. This is because equilibrium is often not achieved in these equipments. It was realized the separation achieved on one stage of tray would not equal to one stage of separation by equilibrium. To achieve a high purity product would require the use of many stages of separation and limited to very small capacity. These early applications required high capital to build and difficult to operate. Engineers began to encountered flow phenomena such as flooding and weeping that do not exist in distillation using stills. This started a continuous effort to develop better distillation equipment by a better understanding of flow phenomena in these equipments. The unanimous goal was to design higher efficiency equipments, achieve higher product capacity, and higher purity product using if possible, less pounds of metal in fabrication.

Two types of liquid flow may exist in the equipment to impede heat and mass transfer. The macro phenomenon is in the bulk flow. One half of the liquid is on the left side of the column and one half is on the right. If the liquid is not collected and remixed on the tray or between the beds, a bulk flow composition difference can exist between the right and left side of the column. The micro phenomenon is in the point flow. Localized mal-distribution causes dead zones on the trays or the packings. This means some of the active sites are not used and ultimately, the overall fractionation capacity is reduced.

2.2. Staged Equipment

The early fractionation trays were developed to mimic the separation process occurring the stills. On each stage, the vapor-liquid mixture attempts to achieve equilibrium, which is the driving force to the components separation. The vapor and liquid will mix to form a layer of froth on the tray. It is within this froth, the turbulence is sufficiently great to enable effective mass transfer. At the edge of the tray, the froth will overflow across a weir and the vapor will disengage itself to move to the tray above. The bulk liquid will flow down to the tray below. This process of mixing into a froth, mass transfer and finally, disengagement will and must be repeated on each stage. If the vapor underneath a tray is insufficient to suspend the froth layer, mixing is poor and liquid can weep to the next tray. If at the downcomer, the froth fails to disengage, then, a continuum exists to the next tray without any further separation. This is call backup. The liquid flow can also be so great that a liquid continuum forms on a tray instead of a vapor-liquid froth. This is called flooding, where little or no separation occurs. These are simple examples of flow phenomena occurring in the distillation equipment that are governed by transport phenomena principles and have little respect to phase equilibria. Weeping, flooding and backup are examples of micro flow phenomena. They can be minimized or prevented by proper operations.

Eddy flow on a tray is a common challenge to tray designers. This micro flow phenomenon occurs because of the round shape of a distillation column. Dye test reveals that the liquid flows in a straight direction across a tray. The liquid at the edges of the tray however, forms an eddy flow path. Where eddies occur, the area becomes a dead zone where there is no separation and reduces the effective active sites on a tray. Designers later placed special valves at the edges to help change the flow pattern. These valves are called "flow directioner", which reduces eddies and effectively increases the efficiency of a tray.

As the liquid flows across a tray, it takes some time before it forms froth and commences mass transfer. This would mean there exist some areas on a tray where there is no separation occurring. To overcome this, special valves are placed under a downcomer. This is called a "bubbling promoter", where more vapor is allowed to flow across creating froth in less flow length. Innovations such as flow directioner and bubbling promoter are designed because engineers recognize the existence of micro flow phenomena.

Correcting them frees up more active sites on a tray, enabling desired separation to be achieved using less trays and promising higher product purity.

Mal-distribution can be caused by the feed and reflux inlet design. A poor inlet nozzle design can affect the efficiency of 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%. A rule of thumb calls for certain distance between a feed nozzle and the next tray because of this flow phenomenon. This has directly caused a column shell to be taller and more expensive to construct. Better-feed nozzle designs are now available to satisfactorily disengage the vapor-liquid mixture in shorter flow length. This allows the use of a shorter column and may increase the overall performance.

Macro flow phenomena are generally not obvious in staged equipment because every tray acts as a recollector where the bulk liquid can fully remixes. However, when a tray has many flow passes, the bulk liquid is divided into different liquid streams and the possibility of the liquid not properly remixed is higher. Some proprietary high capacity tray design has 4 or more flow passes. The liquid flow tends to become more vertical-orientated (between trays) rather than horizontal-orientated (across a tray). It is recognized that despite the higher capacity, these multiple passes tray have lower tray efficiency. The solution is to have more actual stages.

Some flow phenomena occur because of mechanical requirement. In high-pressure application, a tray may need to have additional hold-down and support fixture. These fixtures are not there in a tray design but become necessary during the mechanical design stage. Some times, these fixtures can disrupt the promotion of froth and proper remixing on a tray. If improper remixing occurs, the liquid composition can be varying at different sections of the tray. When propagated to the trays beneath, the effect is same as channeling. The solution to this scenario is the need for chemical engineers to be involved in the mechanical design review. If these disrupting fixtures are found to be necessary, the chemical engineer has a choice to add more stages or choose an alternative tray design.

2.3. Non Staged Equipment

Mass transfer in non-staged equipment follows the same principles as staged equipment. Within the random and structured packing, the bulk liquid is broken into fine droplets to increase the surface area for mass and heat transfer. This appears as a continuous froth across the entire height of the packing bed. The effect of flow phenomena can be more prominent in non-staged equipment as compared to tray applications.

Mal-distribution in the bulk liquid flow, a macro flow phenomenon, can be very pronounced in packings. This is due to the fact that, unlike trayed column, the bulk liquid in a packed column is not collected, mixed and redistributed. The mal-distribution or channeling can caused liquid at different quadrant of the column (but at the same height) to have different liquid composition and densities. Such scenario will also change the flow path of the rising vapor, as different quadrant will have a different path of resistance.

To avoid the loss of efficiency from channeling, the liquid should be collected and re-distributed every 4,572 to 6,096 mm (15 to 20-ft). Above 6,096 mm (20-ft), the channeling becomes high and the efficiency is greatly reduced. The liquid should be collected in a chevron-type collector to evenly distribute the vapor to the next bed. The liquid will remix and evenly re-distributed to the packed bed below with a liquid distributor.

The liquid distribution is a crucial micro flow phenomenon examined closely by many designers. A liquid distributor will shower down the liquid feed at several locations on the top of the packed bed. The liquid needs to travel some distance before meeting and remixes into froth. Thus, a zone of poor mass transfer exists at the top of a packed bed. The challenge is to design suitable liquid distributor to reduce the height of this dead zone. The challenge can be greater if the liquid feed consists of two of more liquid phases with differing densities. The height of the dead zone will be greater if no effort is made to allow pre-mixing of the liquid phases. Special liquid distributors are available to allow pre-mixing of such service. The ability to select the most suitable liquid distributor is crucial and a great testament of a designer's skill.

More often than not, poor mass transfer in non-staged services is caused by construction error. Tower internals must be installed taking particular care to ensure levelness of parting boxes, troughs and similar equipment. In small columns, moderate misalignments may be tolerated, but in large towers, tolerances must be held to no more than +/- 3 mm (1/8-in). If the packings are crushed during the installation, the tower can flood because of reduced open area. In both cases, serious mal-distribution of the vapor and liquid stream will occur initiating both, the macro and micro flow phenomena discussed.

3. CASE STUDY

3.1. Case 1 – Macro Flow Phenomena in Dual Flow Trays

In a Malaysian ethylene plant, a two-column in series C_3 Splitter was constructed to produce polymer grade (99.50 %) propylene. The towers were equipped with 258 dual flow trays. The trays are corrugated into a sinusoidal wave, with alternate trays installed with the waves at right angle.

The propylene service was commissioned in late 1999. It achieved both the nameplate capacity and propylene product quality. Unfortunately, the propylene loss in the propane recycle stream was observed to be significantly higher than the original design heat and material balance. This has resulted in an overall loss in propylene yield, higher purchased energy in the pyrolysis furnace and to a smaller extent, reduced the on-stream factor of the recycle propane gas pyrolysis furnace zone.

During a high load test carried out in July 2000, data was collected to pinpoint the high propylene loss was attributed to lower tray efficiency. By means of simulation to match the plant operating analyses, the efficiency was determined to be in the range of 45%. This is a significantly deviation from the 70% tray efficiency assumed in the design. The tower effectively has less equivalent stages of fractionation and unable to achieve the desired separation. The average propylene in the propane recycle was averaging 45%, much higher that the designed 8%.

A gamma scan on the tower was carried out prior to a shutdown in early 2001 to eliminate potential tray damage. The scan showed all the trays were still intact. However, the liquid density profile showed mal-distribution occurring after the first 30 trays of each column. The decision was made to inspect the column on the results of the gamma scan.

The tower was opened for inspection during the February 2000 turnaround. The trays are intact and level but large 152.4 mm (6") I-beams and U-Channels were found laid perpendicular across the centerline of each tray. The I-beams and U-Channels effectively divided each tray into four quadrants with no chance for re-mixing across the tray.

Figure 1: 6" I-beam installed on the tray.

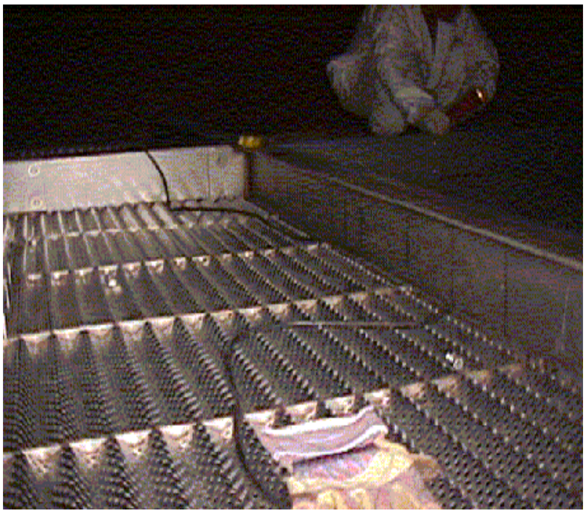


Figure 2: The tray divided into 4 quadrants.

It is important to allow the liquid on each dual flow tray to remix in a form of froth. Without re-mixing, the bulk liquid travels down the column as four different flow paths. Below a certain number of trays, the heavy and light key composition in the four quadrants becomes significantly different.

If the liquid flow was inconsistent across the four quadrants, the gas flow will follow the path of least resistance further reducing the fractionation efficiency. The top of a column will move in a typical meteorological disturbance. This movement will cause the hydraulic load to migrate among the four quadrants. If any hydraulic flow instability were developed it would remain down the column. This hypothesis is consistent with the results from the gamma scan.

A decision was made to install six vapor and liquid re-distributors every thirty trays to correct any mal-distribution that had occurred in the column. Additionally, the U-Channel was constructed in three parts and the middle part of the U-channel was removed on each of the 14th and 15th trays between the re-distributors.

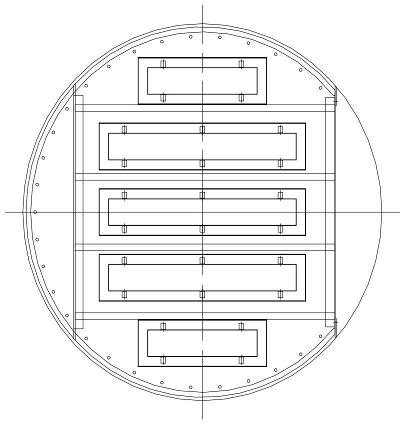


Figure 3: Schematic of Typical Re-Distributor Tray

Figure 4: Picture of a Sulzer Chimney Tray

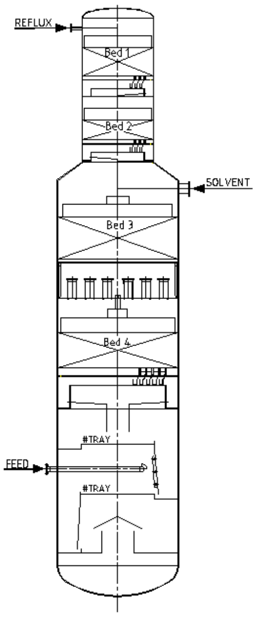
With the addition of these vapor and liquid re-distributors, the tray efficiency of the column was increased 10% resulting in improved fractionation, even with the total reduction in the number of fractionation trays. The propylene in the propane recycle was reduced from 45% to below 10%. The tower maximum capacity achievable before was 112%, and has presently run as high as 115% without reaching a limit.

3.2. Case 2 – Structured Packing

A grass roots extractive distillation BTX unit was commissioned in January 2000. The unit consisted of a Reactor Pretreatment Section, an Extractive Distillation (ED) Column, a Stripper Column, and a Benzene-Toluene Distillation Column. The ED Column has four structured packed sections in the rectifying section (top of the tower) and trays in the stripping section (bottom of the tower). The Stripper Column has one structured packed bed with one tray in the rectifying section and trays in the stripping section.

A test run was performed in July 2000 and plant design criteria were marginally accomplished. A review of the tower internals was completed and recommendations made to improve the distributors and reduce the area of the distributor supports that obstructed the packing.

In January 2001, with the turn around of the Ethylene Cracker, the recommended modifications were installed. With the modifications to the distributors and retraying a limiting stripping section, all the plant design criteria were met. Additionally an 18% increase in aromatic production capacity was achieved while improving aromatic recoveries.



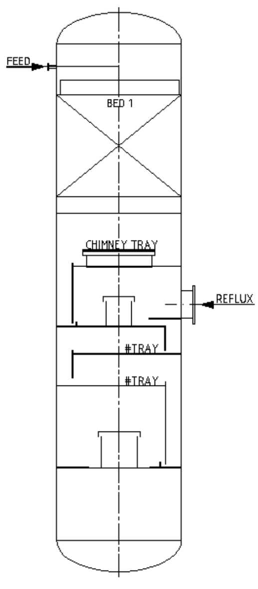


Figure 5: ED Column Stripper Column

3.2.1. Micro Flow Phenomena Case

A team of maintenance and engineering personnel, that included the authors, were able to inspect the ED Column and Stripper Column in May 2000. The columns were found to be clean and well constructed. The design was similar to those that the technology licensee had utilized in the past with success. It is acceptable to utilize past designs only if they conform to basic engineering fundamentals.

The first opportunity found was at the top of the third bed of the ED Column, counting from the top down. This was the lean solvent feed point. The liquid distributor had two issues. The first issue was that 101.6 mm by 203.2 mm (4" x 8") plates on top of the packing supported the distributor. These plates covered 8% of the packing.

The four by eight-inch plate blocks the rising vapor flow and sets up a channeling regimen, negating the effect of the distributor. The plates are blocking the gas flow underneath and the vapor below the plates is channeled to the side. A reduced separation or heat exchange efficiency is induced and column capacity may be reduced.

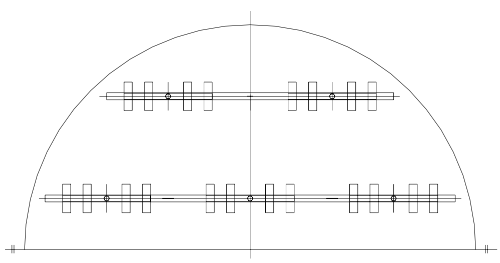


Figure 6: Schematic of Distributor Support Plate

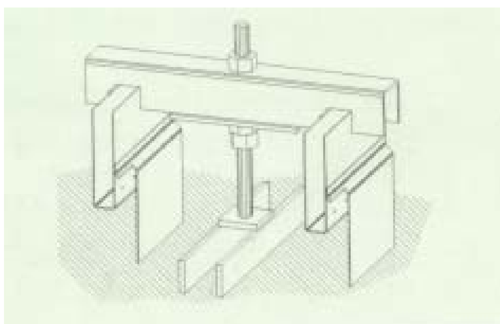


Figure 7: Schematic of New Distributor Support Plates

The liquid redistributor support was redesigned using thin square bar stock to support the distributor in two parallel strips across the top of the packing. This reduced the blocked area of the packing too less than 1%. This one change greatly increases the distillation capacity of the packing.

The second opportunity was in the lean solvent distributor itself. At this point, the distributor had two feeds. The first was from the second bed of packing, which was mostly hydrocarbon, and the second was from the lean solvent feed point. The distributor essentially functioned as two distributors in parallel; no premixing of the feeds to the third bed was preformed. This meant that the hydrocarbon from the second bed and the lean solvent did not begin to contact until several feed down the bed of the packing.

The distributor was reconfigured to allow the hydrocarbon and the lean solvent to premix as they left the distributor. Each distributor box had dual compartments that released the different phases to mix above the packing. This enhanced the solvent's ability to be more selective toward the aromatics.

At this point, there are three phases in the packing; vapor which should be mostly non-aromatics, hydrocarbon liquid that should be a mixture of aromatics and non-aromatics, and solvent. Improved mixing of the phases should lead to increase in mass transfer.

Figure 8: Picture of dual compartment distributor being tested at Sulzer Test Rig in Singapore

3.2.2. Macro Flow Phenomena Case

The macro opportunity was found at the bottom of the third bed of the ED Column. The bottom of the third bed did not have a liquid collector. The liquid was allowed to freely rain down on next chimney tray, setting up the macro phenomena. A liquid collector-distributor has two functions. First is to collect, mix and route the liquid to the next bed, whereas, second is to evenly distribute the vapor across the upper bed section. In some cases without a collector, the vapor may be channeled leading to reduced packing efficiency. Vapor distribution is required when there is not sufficient height between the beds for vapor mixing, in high-pressure applications where gas densities are high, and where there is a small gas to liquid density ratio.

The packing was removed from the third bed and a liquid collector was installed. The well-mixed liquid was collected and routed to the fourth bed liquid distributor, and the vapor was evenly distributed to the packing above the collector.

The unit was commissioned in February 2001 and a high load test was preformed in May 2001. The unit has yet to reach its limit due to feedstock constraints. Below is a table comparing the July 2000 test run with the May 2001 test run.

Test Run	Design	15 July 2000	15 May 2001
Unit Feed Rate, ton/hr	27.55	27.17	33.78
Benzene Recovery, %	97.0	95.7	97.27
Toluene Recovery, %	98.0	98.7	98.69
Benzene Product, ton/hr	10.78	13.14	15.07
Toluene Product, ton/hr	5.61	4.83	6.32
Non Aromatics, ton/hr	7.25	6.29	7.12
Benzene in Non Aromatics, Wt %	<5	5.1	3.1
Benzene Purity, %	99.90	99.95	99.98
Toluene Purity, %	98.50	98.78	98.70

Table 1: Performance of the BTX unit before and after the modifications.

4. LESSONS LEARNED

Undesired flow phenomena in distillation equipments can cause loss of fractionation efficiency, capacity and more importantly, loss of business opportunity. They can be caused by poor decisions made during the design phase, lack of designers' knowledge on the solutions that are available and in some cases, due to construction error. It is important for chemical engineers from both the engineering and operations function to participate in the conceptual design, basic and detailed engineering. Error eliminated at this stage will minimize the possible monetary loss. It is crucial for chemical engineers to participate critically in the mechanical design review.

Engineers must continuously seek knowledge of newer technologies and solutions. It is a good practice to document any design/construction failures and share with the chemical engineering community of both industry and academic fields. Learning not to repeat others' mistakes is a great improvement effort.

There is a need for chemical engineers trained in design and commissioning skills to contribute in the construction phase. Proper inspection and punch-list prior to pre-commissioning can help to resolve construction deficiencies. This can minimize the possibility of costly variation orders and business interruption.

If a distillation system cannot perform as per the design after commissioning, there is a need to carry out trouble-shooting and identify the problem in the shortest time frame. Review of mechanical drawings and shutdown inspection can identify design deficiency. Gamma scan can identify construction errors. Chemical engineers play the most crucial role of deciding whether modification is required or just live with the problem. Many of these roles of a chemical engineer, bears no whatsoever relationship to his knowledge of phase equilibria. Nevertheless, a well-trained chemical engineer is the only person competent to make these crucial decisions from his understanding of flow phenomena.

5. CONCLUSIONS

Undesired flow phenomena in distillation equipments can cause loss of fractionation efficiency, capacity and more importantly, loss of business opportunity. Macro flow phenomena occur when the bulk liquid fails to remix properly causing mal-distribution. Micro flow phenomena occur when localized mal-distribution exist causing dead zones in the column. Flow phenomena can be minimized or eliminated by critical participation of competent chemical engineers in the engineering, construction and commissioning phase. If flow phenomena are found after commissioning, chemical engineers must take the lead to resolve the issue to minimize further loss from business interruption.

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