Enhancing fractionator efficiency

Properly designed vapour and liquid distribution devices enable more effective distillation column efficiency

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Number of trays and packed bed height are both primary parameters in determining the degree of separation of a distillation column. However, this factor alone cannot guarantee targeted distillation column efficiency. Vapour and liquid distribution devices play a vital role and overlooking these critical items often brings inferior results. The importance of vapour and liquid distribution design is more emphasised for a packed column where column efficiency is more sensitive to liquid and vapour distribution.

This article will discuss commonly overlooked items in vapour and liquid distribution devices. Actual retrofits for packed fractionators, which examine how column efficiency enhancements are achieved through careful analysis and design procedures, are demonstrated through two case studies: a crude atmospheric column in a petroleum refinery and a demethaniser in a natural gas processing plant. Useful methodologies for evaluating vapour and liquid devices and for remedies are also illustrated.

Liquid distribution devices
The correct selection of a liquid distributor type is the first step for reliable liquid distributor design. The selection of the liquid distributor type requires extensive application know-how and should be customised for each service section. A refinery vacuum column is a good example that emphasises the importance of a liquid distributor type.

A refinery vacuum column is commonly configured with structured and/or grid packing to handle high amounts of vapour traffic with a minimum column pressure drop. In past designs, many equipment suppliers have selected a spray nozzle distributor coupled with a mist eliminator in this section as it is primarily utilised for heat transfer. However, spray nozzle distributors may cause significant liquid entrainment and a loss of top distillate yield. Switching the distributor type with a gravity flow trough-style liquid distributor can reduce the chances of liquid entrainment. A mist eliminator is unnecessary in this configuration; in fact, additional pressure drop can be eliminated by removing the mist eliminator. Meanwhile, the refinery vacuum tower wash section’s flow regime is characterised with much lower liquid traffic compared to the neighbouring pumparound section. Selection of a gravity flow trough-style liquid distributor can reduce the chances of liquid entrainment. A mist eliminator is unnecessary in this configuration; in fact, additional pressure drop can be eliminated by removing the mist eliminator.

Fouling tendency is often ignored in liquid distributor design. The basic equation used to size gravity liquid distributors is:

$$H = \left( \frac{L_v}{k \times N \times HA} \right)^2$$

$H$ = liquid height (‘head’) above distributor orifices
$L_v$ = liquid volumetric flow
$N$ = number of orifices
$HA$ = hole area
$k$ = orifice coefficient

A minimum liquid height ($H$) must be maintained to ensure uniform liquid distribution. In addition, a minimum number of orifices ($N$) should also be maintained to ensure good distribution (usually referred to as ‘drip-point-density’ in the number of holes per unit cross-sectional area). These concerns would tend to push the designer to use a greater quantity of small orifices. However, this design approach opens the risk of fouling the liquid distributor. A device designer’s application knowledge and experience are critical for the correct hole size against liquid distributor fouling.

The pattern of the liquid distribution points is also critical to achieve a good packed bed efficiency. A distribution quality rating index was developed to gauge the quality of liquid distribution. A lower rating index of distribution quality can downgrade packed bed efficiency. Recent pilot plant testing and analysis verifies that packed bed efficiency is noticeably

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PTQ Q2 2016 59
influenced by the pattern of liquid distribution points. The importance of initial distribution before entering the liquid distributor device cannot be over-emphasised. Improper pipe distributor or gravity down pipe/box design can affect liquid distributor performance adversely. It is observed that initial liquid maldistribution to a primary parting box of a gravity flow trough type distributor causes liquid splashing and poor liquid distribution performance.

The unnecessarily wide operating range requirements of a liquid distributor can downgrade liquid distribution quality. The multi-stage orifice hole design concept is commonly selected for wide operating range liquid distributor design. Flow instability between the orifice hole stage can cause high flow deviation, which can downgrade liquid distribution quality. The wide operating range requirement of the liquid distributor also affects pre-distribution quality. The perforated pipe distributor or gravity downpipe/box is usually arranged as a pre-distribution device. A liquid phase perforated inlet pipe distributor has been traditionally designed with maximum liquid velocity criteria in order to avoid mist formation. Meanwhile, lower velocity issues are often overlooked during turndown operations. Insufficient perforated hole liquid velocity does not maintain enough pressure drop for uniform liquid distribution and can result in poor initial liquid distribution.

It is often perceived that the operating range of distillation equipment should be matched to distillation column feed/product ranges in the industry. This misunderstanding requires a wide operating range of the liquid distributor device and results in poor liquid distribution performance in the target operating point. As the traffic range of the liquid distributor device does not have to be matched to column feed/product ranges, adjusting the reflux/boil-up ratio or heat balance using pumparound shifting at an extremely low level of operating mode can allow normal operating range selection of the liquid distributor. This strategy increases energy consumption at an extremely low level of operating mode but can secure efficient performance within the operating range. Unless unit operating ranges are significantly swung in a short time span, this strategy provides better overall plant performance/economics.

Vapour distribution devices
A collector tray is a common device for an intermediate stream draw-out of a distillation column, such as a refinery multi-product fractionator. It is well known that a collector tray is needed for the successful function of liquid collection. On the other hand, it is not well recognised that collector trays affect vapour distribution throughout the column. Vapour distribution is an important factor to ensure desired column efficiency. Ignoring this factor can cause vapour maldistribution and result in downgrading column performance. Vapour maldistribution can also cause liquid maldistribution due to an uneven packing void area. Eventually packed bed performance can be downgraded.

A hypothetical angle construction is a useful tool to gauge vapour distribution performance. A wide hypothetical angle between the vapour riser hat and packed bed above has a higher risk of vapour maldistribution. The vapour escaping pattern from the collector tray is also critical to ensure appropriate vapour distribution. Collector trays are usually equipped with vapour riser hats to prevent process liquid raining down through vapour risers. The vapour streams escape between the hat and the top of the vapour riser. If this area is too narrow, excessive pressure drop and/or liquid entrainment can occur and the column performance can be adversely affected. Inadequate vapour riser opening and liquid guide geometries can accelerate liquid entrainment.

The importance of initial distribution before entering the liquid distributor device cannot be over-emphasised

The construction method of collector trays should be selected carefully. Liquid leakage through collector tray joints and/or in between collector trays and support members can influence column performance adversely. This trouble is aggravated when the total draw-off collector tray is arranged with a high liquid level. Loss of production, loss of degree of separation, poor reboiler performance and undesired heat balance shifting are common symptoms. A seal welded construction method is strongly required for the total draw-off collector tray. A gasket is sometimes applied for construction and maintenance convenience. However, using a gasket does not ensure a leak-free collector tray, especially in a severe temperature and/or corrosive service environment.

Thermal expansion of collector trays is an issue when the difference in metal thermal expansion coefficients between collector tray metallurgy and column shell metallurgy is significant. A thermally expanded collector tray with seal welded construction can cause mechanical damage to a column shell and/or collector tray. Collector trays should be designed with consideration for thermal expansion in this condition. Leak-free performance and mechanical rigidity of collector trays should not be ignored during design.

Two actual retrofit case studies demonstrate how packed fractionator efficiencies are improved through corrected liquid and vapour distribution.

Case study 1: crude atmospheric column background
The crude atmospheric column in this case was commissioned as a fully structured packed fractionator excluding the bottom stripping section. Additionally, four side
strippers were included in the crude distillation unit. The heavy kerosene side stripper has been designed with a structured packed bed unlike the other three side strippers. After commissioning of the crude distillation unit, the top fractionation packed bed was converted to fixed valve trays in order to improve the equipment’s resistance against hydrochloric acid corrosion and ammonium salt fouling. Figure 1 illustrates the crude atmospheric column configuration. Desalted crudes are charged and heated through two parallel preheat trains and furnaces before entering the crude atmospheric column. This column fractionates the charged crude oils into intermediate rundown products: unstabilised naphtha, light kerosene, heavy kerosene, light gas oil, heavy gas oil and atmospheric residue. Two pumparound circuits are arranged at the light kerosene and light gas oil boiling range material locations.

As the heavy kerosene intermediate product is used for fighter-grade aviation fuel production, controlling flash and freezing points is critical to achieve target heavy kerosene yield. It requires sharp fractionation performance among heavy kerosene and neighbouring intermediate products to control front and rear ends of the heavy kerosene intermediate product.

Since the commissioning of the crude distillation unit, poor fractionation efficiency had been experienced, especially among light kerosene, heavy kerosene and light gas oil intermediate products in the crude atmospheric column. The pre-revamp crude assay and actual product yield structures are graphically compared in Figure 2. The crude assay indicates recoverable material yield with a clear-cut basis among products. These graphs show that a substantial amount of heavy kerosene boiling range materials were downgraded to neighbouring products. This poor fractionation performance limited heavy kerosene yield and downgraded refinery economics.

Structured packing damage and/or corrosion were initially suspected as a root cause of the trouble. All structured packing elements installed originally were replaced by new ones. However, the replacements did not improve the column fractionation efficiency.

Case study 1: root cause identification

Dedicated overall system troubleshooting and process evaluations were conducted to identify the root causes.

There was no flooding symptom or capacity limit indication during the crude atmospheric column operation. Measured pressure drop values across the column were similar to the design values. As part of the troubleshooting activities, internal reflux rates for fractionation sections were increased through shifting pumparound balances. It was found that increased internal reflux rates did not enhance fractionation performances.

In order to quantify vapour and
liquid traffic values in the column, a process simulation model was constructed with base operating conditions. These operating data were gathered through pertinent test runs of the crude distillation unit. Structured packing hydraulic capacities were verified with the column internal vapour and liquid traffic profiles quantified through simulation modelling. Calculated structured packing capacity for each bed did not reach the capacity limitation point. Instead, simulation modelling identified poor efficiencies in the packed beds for fractionation services. Simulated packing efficiencies were much lower than typical efficiency values observed in crude atmospheric column services.

The original liquid and vapour distribution device designs were reviewed thoroughly. Collector trays positioned underneath the structured packing not only functioned as liquid collection devices, but also as vapour distribution devices. The hypothetical angle of vapour distribution was constructed in the original collector tray to gauge vapour distribution performance. The calculated 70° hypothetical angle was too wide to ensure adequate vapour distribution for the target packed bed performance.

Another design flaw found in the original devices was a poor initial liquid distribution system from the collector tray to the liquid distributor. Since the crude atmospheric column diameter is quite large, the gravity flow trough-style liquid distributors for packed beds were configured with two primary parting boxes. After side stream liquid draw-off, the remaining liquid rates at the collector tray were transported through multiple gravity downpipes to the liquid distributor primary parting boxes. It was found that these downpipes were flushed at the collector tray deck. Liquid rates into downpipes were uncontrollable using a design of unraised downpipes over the collector tray deck. Uniform liquid distribution at the liquid distributor primary parting boxes could not be secured. Regardless of liquid distributor design, liquid distribution quality and fractionation efficiency could be downgraded. It was also detected that flow deviations among secondary troughs were unacceptably high in the original liquid distributor design. These high flow deviations can aggravate liquid distribution qualities. Figure 3 illustrates design flaws in the original collector tray and liquid distributor design in the crude atmospheric column.

A pan type liquid distributor was installed in the heavy kerosene side stripper. Inadequate liquid irrigation drip point patterns were observed in the original distributor design. The calculated distributor rating index was too low to achieve the desired liquid distribution quality. It could cause poor liquid distribution quality for heavy kerosene stripping service.

Case study 1: equipment modification
Based on the aforementioned process evaluation and root cause parameter Pre-revamp test run Post-revamp test run

<table>
<thead>
<tr>
<th>Case parameter</th>
<th>Pre-revamp test run</th>
<th>Post-revamp test run</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yield structure</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Crude charge, LV%</td>
<td>Base</td>
<td>∆ 0%</td>
</tr>
<tr>
<td>Light kerosene, LV%</td>
<td>Base</td>
<td>- ∆ 0.3 LV%</td>
</tr>
<tr>
<td>Heavy kerosene, LV%</td>
<td>Base</td>
<td>+ ∆ 3.4 LV%</td>
</tr>
<tr>
<td>Light gas oil, LV%</td>
<td>Base</td>
<td>+ ∆ 1.0 LV%</td>
</tr>
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<td>Heavy gas oil, LV%</td>
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<td>- ∆ 0.9 LV%</td>
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<tr>
<td>Operating parameter</td>
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<tr>
<td>Overflash rate, % of total distillate</td>
<td>Base</td>
<td>- ∆ 3%</td>
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<tr>
<td>Unit stripping steam light kerosene stripper, lb/BBL</td>
<td>Base</td>
<td>- ∆ 89%</td>
</tr>
<tr>
<td>Unit stripping steam heavy kerosene stripper, lb/BBL</td>
<td>Base</td>
<td>- ∆ 26%</td>
</tr>
<tr>
<td>Fractionation performance</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Light kerosene 5% - naphtha 95%, °F</td>
<td>Base</td>
<td>+ ∆ 2.0°F</td>
</tr>
<tr>
<td>Light kerosene flash point, °F</td>
<td>Base</td>
<td>+ ∆ 7.2°F</td>
</tr>
<tr>
<td>Heavy kerosene 5% - light kerosene 95%, °F</td>
<td>Base</td>
<td>+ ∆ 11.0°F</td>
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<tr>
<td>Heavy kerosene flash point, °F</td>
<td>Base</td>
<td>+ ∆ 5.4°F</td>
</tr>
<tr>
<td>LGO 5% - heavy kerosene 95%, °F</td>
<td>Base</td>
<td>+ ∆ 95.4°F</td>
</tr>
</tbody>
</table>

Note 1. ASTM D86 (LV%)
consumption rate and lower over-flash rate are achieved although distillation gap values among products are enhanced with higher heavy kerosene yields. The reduced amount of overflash indicates that internal reflux rates for the fractionation sections are not increased and verifies that improvement in fractionation efficiency is not gained by higher internal reflux ratios. Simulation modelling with post-revamp test run conditions was conducted to quantify improvements in packed bed efficiency. Each fractionation packed bed efficiency is expressed as HETP (height equivalent to one theoretical plate). Simulated fractionation bed efficiencies between pre- and post-revamp cases are compared in Table 2. This table reveals that poor packed bed efficiencies are corrected even though all structured packing elements are reused.

**Table 2**

<table>
<thead>
<tr>
<th>Section</th>
<th>SSA ft²/ft³</th>
<th>Pre-revamp</th>
<th>Post-revamp</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light kerosene/heavy kerosene</td>
<td>38 (125)</td>
<td>154°</td>
<td>51°</td>
</tr>
<tr>
<td>Heavy kerosene/LGO fractionation</td>
<td>52 (170)</td>
<td>110°</td>
<td>22°</td>
</tr>
<tr>
<td>LGO/HGO fractionation</td>
<td>52 (170)</td>
<td>152°</td>
<td>38°</td>
</tr>
<tr>
<td>Wash</td>
<td>107 (350)</td>
<td>41°</td>
<td>21°</td>
</tr>
<tr>
<td>Heavy kerosene side stripping</td>
<td>38 (125)</td>
<td>68°</td>
<td>41°</td>
</tr>
</tbody>
</table>

**Note**
1. Structured packing nominal specific surface area
2. Angle from X-axis

To improve vapour distribution, new collector trays were designed with a narrow hypothetical angle. Downpipes bridging the collector tray and liquid distributor were raised over the collector tray deck in order to split liquid evenly to the two primary parting boxes of the liquid distributor. Flow deviations among secondary troughs of the liquid distributor were minimised to improve distribution qualities and drip point patterns were rearranged in the heavy kerosene side stripper liquid distributor.

**Case study 1: performance summary**

Post-revamp performance results are summarised and compared with pre-revamp performance results in Table 1. Crude slate composition and charge rates are unchanged between pre- and post-revamp test runs. The modified crude atmospheric column produces much higher heavy kerosene yields. The column fractionation efficiencies are significantly improved. The lower heavy kerosene side stripping steam

**Figure 4** Case study 2: demethaniser configuration
Case study 2: root cause identification

Demethaniser simulation models were constructed with two different operating conditions, summarised in Table 3. It was observed that simulated side reboiler duty of a higher feed case was lower than that of a lower feed rate case. This limited boil-up through a side reboiler possibly downgraded the degree of separation of the column. Measured column degrees of separation and other key operating parameters were reasonably matched between operating conditions and simulation results.

Rigorous process and equipment evaluation showed that the original side reboiler heat exchanger equipment did not cause limitation of performance. The horizontal type thermosyphonic heat exchanger design and pressure drop profile through the reboiling side circuit were adequate to achieve the desired side reboiling performances. Installed random packing type and packed bed heights for the column were acceptable to meet target capacity and degree of separation. However, it was found the original collector tray underneath the top packed bed was not properly designed. The vapour riser heights were not tall enough to maintain the desired liquid hold-up. This insufficient height could cause liquid overflowing through the vapour risers. Eventually the side reboiler inlet liquid flow could be reduced. The liquid overflow also quenched the bottom packed bed. Moreover, the original collector tray was designed with bolting construction instead of the seal welding method required for the service. This bolted method could cause liquid leakage and could aggravate lower column bottom temperature and limit side reboiler inlet flow rate.

The original liquid distributors were also reviewed; a low distributor rating index was the result of the original liquid distributor design. Although not a primary root cause, poor distributor design decreased performance further.

Case study 2: equipment modification

The collector tray design was corrected underneath the top packed bed. The height of the vapour riser was increased to prevent liquid overflowing. The original bolting construction was converted to seal welded construction to minimise the chance of liquid leakage. Drip point patterns of both packed bed liquid distributors were rearranged to improve uniformity of liquid distribution.

Another goal of the column retrofit was to increase the column capacity. Process evaluation showed that the original random packing size for the top packed bed was not suitable and a larger size of random packing was required. The one-step larger size was
applied and verified to meet the target degree of separation.

**Case study 2: performance summary**

Pre- and post-retrofit performances are summarised in Table 4. C₂ and C₃ component recovery percentages to the bottom product are substantially improved at an even higher feed rate. The trouble with lower column bottom temperature is also solved. C₂ component recovery percentages at various feed rates are plotted in Figure 5. This performance trend chart shows that post-retrofit C₂ component recoveries are noticeably improved and enhanced C₃ component recoveries are maintained at higher feed rate operations. This chart shows that pre-retrofit C₂ recoveries were substantially downgraded at a higher feed rate.

Like the first case study in this article, simulation modelling with post-retrofit conditions was conducted to quantify packed bed efficiency improvements. Table 5 summarises and compares simulated packed bed efficiencies between pre- and post-retrofit cases. Top packed bed efficiency is enhanced in spite of implementation of a larger random packing size.

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**References**


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<table>
<thead>
<tr>
<th>Table 5</th>
<th>Case study 2 packed bed efficiency comparison</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Section</strong></td>
<td><strong>Pre-retrofit packing nominal size</strong></td>
</tr>
<tr>
<td>Top-above side reboiling</td>
<td>5/8”</td>
</tr>
<tr>
<td>Bottom-below side reboiling</td>
<td>5/8”</td>
</tr>
</tbody>
</table>