Optimizing crude unit design

Real retrofit examples demonstrate how crude units can be successfully optimized with the crude slates currently being processed. Process design strategies are discussed in detail and highlight how retrofit targets are achieved.

Introduction

The basic function of a crude distillation unit (CDU) is to provide initial separation of the crude oil feed mixture into the desired fractions to be further processed in the downstream units. The crude unit’s quality of performance impacts heavily on the downstream unit’s performance. A lot of crude units currently operate with different feed slates to their original feed specifications. This change in feed composition often results in inferior crude unit performance and reduces the unit’s run length. Re-optimising the design and operation of the crude unit with current feed slates is essential to maximize a refiner’s economics. In addition, recent crude oil price fluctuations and increased economic pressure further emphasise the importance of optimizing crude unit performance.

Crude atmospheric column

The crude atmospheric column is the CDU’s core piece of equipment. In a typical crude unit design, crude oil is heated and introduced to the crude atmospheric column’s flash zone. The light products are typically recovered as distillates from multiple liquid product draws and the remaining crude is discharged at the column’s bottom. The original process arrangement relied on a single top reflux flow. The column top reflux provided condensation for all the required product draws, plus the overflash. This approach created high variations in the internal vapour-liquid traffic throughout the column (from column top to flash zone), with a maximum reflux loading at the top and the lower wash section receiving only a small amount of liquid, wash oil. The columns were then sized according to the greatest load, top section internal traffic, which resulted in an oversized column diameter. Moreover, the required size of the overhead condenser was substantially increased.

Figure 1  Comparison of internal-reflux rates for three methods of providing reflux
To minimise these liquid traffic variations, inter-condenser design philosophy was adapted in the crude atmospheric column design. Intercondensers can be configured as either pumpback or pumparound circuits. Figure 1 compares typical internal reflux rate variations through the crude atmospheric column (from column top to flash zone) among three reflux methods. The pumparound reflux method achieves more uniform liquid balancing through the column than the other two reflux methods. This uniformity of liquid enables the column to be sized at a smaller diameter for reduced investment cost. The higher pumparound draw temperatures increase the opportunity for heat recovery for lower energy consumption. In addition, the overhead condenser size is reduced. The main trade-off is that the pumparound circuit design requires more trays and/or packing for heat transfer performance. In summary, the advantages of the pumparound reflux arrangements far outweigh any disadvantages, and as a result it has replaced the pumpback reflux method in most modern crude atmospheric column designs.

The presence of a top pumparound circuit depends on overhead distillate yield/fractionation requirements, column top temperature control and overhead condenser size/limitations. Typical crude atmospheric column overhead configurations are depicted in Figure 2 for cases A-C. Case A shows that the top section reflux is provided by a top pumparound circuit only. In this configuration, the column top temperature is relatively high and the chance of water condensing at the column top can be minimized. In addition, the overhead condenser size can be minimized due to a lack of top reflux stream. However, the top pumparound trays and/or packing do not contribute towards fractionation.
An additional fractionation section is required to achieve the desired fractionation between the overhead distillate and the first side product, which increases the overall column height.

Case B depicts a crude atmospheric top section with a top reflux without a top pumparound circuit. This top reflux temperature is usually lower than the reflux through the top pumparound circuit. In this case, fractionation performance between the overhead distillate and the first side product can be maximized at the given column height. However, the required overhead condenser duty is higher and the column top temperature is lower than for Case A.

Case C is somewhat of a compromising design between Cases A and B. This configuration has a top reflux irrigation line as well as a top pumparound circuit. The amount of cold reflux (from top reflux) and hot reflux (from top pumparound) can be controlled at given processing conditions. This configuration is suitable for the crude atmospheric column, which faces high variations in overhead distillates and yields.

Crude column internal vapour and liquid traffic rely heavily on pumparound circuit locations. The number and location of pumparound circuits are determined by crude slate structures, product yield patterns, fractionation requirements, overhead condenser size and other factors. The crude atmospheric column is designed to provide the best performance for specific ranges of crude slates and product yields. Therefore, a large change from design conditions may induce performance downgrading in the crude unit. Fractionation performance between adjacent products requires specific design internal reflux at a given number of fractionating trays or packed bed depth. Crude overhead condenser duty is also determined by design heat balances.

In most cases, the actual crude slate structures processed in the crude unit deviate from the original design ranges. To maintain desired unit performances at changed feed conditions, most refiners adjust and rearrange the pumparound balances. These operation parameter changes shift the column traffic through the crude atmospheric column. The pumparound rate change impacts neighboring fractionation section internal reflux rates, so fractionation performance is affected. Unbalanced column traffic often results in unit capacity limitations. The crude atmospheric column design should be re-evaluated with current operating blends to ensure the best performance possible.

The following actual retrofit case demonstrates how a crude unit can be successfully optimized, considering a more typical crude blend used by the refinery.

**Retrofit background**

The crude unit under discussion was originally commissioned in the early 1970s. Charged crudes are heated through two parallel preheat trains and furnaces, and then introduced into the crude atmospheric column. This column separates crudes to intermediate products: unstabilised naphtha, kerosene, light gas oil (LGO), medium gas oil (MGO), heavy gas oil (HGO) and reduced crude
(R/C). Unstabilised naphtha is then fed to the naphtha stabilizer to separate the LPG and naphtha. The kerosene stream is transported to the hydrotreating unit. LGO, MGO and HGO are combined to the diesel pool after hydrotreating. Reduced crude is either transported to conversion units or blended to fuel oil.

The crude atmospheric column was originally constructed with four pumparound circuits: one top pumparound and three diesel pumparound circuits. A top reflux stream, which is recycled from the unstabilized naphtha (overhead distillate), is combined with the top pumparound stream before returning to the crude atmospheric column. The amount of top reflux stream is adjusted relative to the unstabilised naphtha boiling range of the processed crudes.

To increase the crude charge rate and enhance unit performance, this crude unit had been previously retrofitted. During these prior retrofits, the HGO pumparound and wash sections were converted to structured packed beds. All four side strippers are steam-stripped. Figure 3 illustrates the crude atmospheric column configurations after these previous retrofits.

To meet required downstream unit balances, especially in the conversion units, the refiner decided to perform a new crude unit retrofit. The targets of this current retrofit were debottlenecking operating limitations and increasing crude unit capacity. One of the unit limitations the refiner faced was that the crude atmospheric column had difficulty processing crude slates containing a high percentage...
of kerosene boiling range materials. In the winter, kerosene product is usually more valuable than diesel and naphtha. Relieving any limitations on kerosene production was necessary to improve unit economics.

Replacing existing crude column trays with high-performance trays or packing is one of the most economical ways to improve column capacity in terms of overall downtime and cost. However, the preliminary evaluation was that a retrofit of the kerosene side stripper would not meet the required capacity. All four existing side strippers were stacked and erected as one single column shell with the kerosene stripper located on top. Therefore, it was not feasible to modify the shell/vessel to change the kerosene side stripper design only. Plot space and access to the unit were limited too, so adding and/or replacing the side strippers was impossible without substantial cost.

**Test run and unit performance evaluation**

Prior to any process evaluation, a dedicated crude unit test run was conducted to gather pertinent operating data. The importance of a test run cannot be stressed enough. Daily operating data do not always provide all the required information for reliable process evaluations. A crude slate containing high kerosene boiling range material was selected for the test run, as this represented a typical operating crude slate in the unit. For equipment limitation checking, the test run charge rate was determined as the maximum crude charge rate in which the crude unit operated without loss of fractionation efficiency.

In order to gather pertinent operating data, all associated instruments were calibrated prior to the test run. The measured flow rates were verified via flow meter orifice calculations and storage tankage levels, to establish whether mass balance closure error was within suitable range for reliable modelling. Traditional laboratory methods do not provide appropriate characterisation for heavy oil boiling range material. The high temperature simulated distillation (HTSD) method was used for the reduced crude stream laboratory test to obtain better heavy boiling range material characterisation.

Since distillation equipment pressure drop is related to column traffic, a survey of measured pressure drops across the column was required. This is a useful tool in column troubleshooting and evaluation. In particular, the survey allows the troubleshooter to pinpoint equipment locations that require further evaluation. The measured pressure drop profile through the column showed that the top pumparound pressure drop was over two times higher than the LGO and MGO pumparound section pressure drop on the same basis. In addition, the measured HGO packed bed pressure drop was much higher than expected. This pressure drop survey indicated that the column top and bottom sections might be more loaded than the middle sections.

Reliable simulation modelling is another cornerstone of successful process evaluation. Throughout the modern hydrocarbon industry, simulation is widely used to design and/or analyse distillation column performance and it has become a basic tool for process engineering. Many design firms rely heavily
on simulation modelling to establish heat and material balances. Commercially available steady-state process simulators are regularly upgraded with regards to thermodynamic packages, component and property databases, properties calculation, numerical method algorithms, software interfaces and other capabilities.

Nevertheless, selecting reputable simulation software does not guarantee the reliability of simulation modelling. Accurate simulation modelling still requires extensive knowledge and understanding of the process and equipment that need to be modelled. Inherent gaps between actual condition and theoretical simulation modelling should not be overlooked. It has been observed that unreliable simulation modelling that neglects these issues can lead to design flaws and performance deterioration. In an earlier article, it was discussed that conventional flowsheeting topology does not adequately address refinery fractionators such as crude vacuum distillation columns. Actual flash zones operate in a nonequilibrium state, and fluid mixing through transfer lines is highly nonideal. Conventional simulation topology commonly used in the industry does not predict crude column performance properly. This especially applies to the flash zone, transfer line, and wash and stripping sections.

During this crude atmospheric column simulation modelling, it was observed that conventional topology did not properly simulate energy loss through the transfer lines. Therefore, process solutions based on conventional simulation potentially under- or overpredict operating parameters. Such results may induce a performance shortfall or failure in a retrofit solution. To obtain reliable simulation modelling results, this crude atmospheric column was modelled using modified simulation topology. This updated modelling procedure dissected the column into multiple blocks to model the crude

![Comparison of crude slate structure](image)
atmospheric column, the furnaces and the transfer line properly. The interval of pseudo components was adjusted to match the obtained laboratory distillation temperature span. Tray efficiency for each fractionation section was determined through various sensitivity analyses.

**Root cause identification**

This crude unit was originally designed and constructed to process high diesel and low kerosene content crude slates. That is why three pumparound circuits were located in the diesel section, while a pumparound circuit was omitted in the kerosene section. The design philosophy in this crude unit showed the best performance with diesel-rich and kerosene-poor crude slates.

For the first step of root cause identification, the crude slate structure for the test run was compared with previous retrofit design crude slates. The test run crude and previous crude yield structure are illustrated in Figure 4. These yield structures were obtained using blending programs. The blending program predicts recoverable material yield with a clear-cut basis between products and does not take into consideration actual distillation column performance. Nevertheless, this crude structure comparison helps comprehend any deviation between the prior design and current operation environment. This graph shows that the test run crude slate contains much more kerosene boiling range materials than the previous retrofit design crudes. Petroleum gas and naphtha content were also increased in the test run crude slate, while diesel boiling range material percentages are almost the same for the two crude slates.
To scrutinize unit limitation and identify the root cause, the column traffic profiles were reviewed at the test run conditions. Existing tray and packing capacities for the test run case were calculated with simulated traffic extracted from the test run simulation. In Figure 5, the red line indicates simulated pumparound capacity at the test run condition. Capacities of previous retrofit design cases are plotted in green. These plots show that the top and HGO pumparound sections were run at high capacities, while the LGO and MGO pumparound sections were run at lower capacities. Relative loads among the four pumparound circuits were not optimized at the previous retrofit design stage, so this problem was exaggerated due to the current high kerosene crude slates.

One of the ways to improve pumparound balancing is to shift the top and HGO pumparound loads to LGO and MGO pumparound circuits. However, simple pumparound rate redistribution will impact fractionation in the existing column arrangement. Vapour and liquid traffic is decreased above the section where the pumparound rate is increased. In this particular column, increasing the LGO and/or MGO pumparound rates would result in a reduction in the internal reflux of the naphtha-kerosene fractionation section and downgrade the separation between these products. One possible result is a reduced kerosene flash point and difficulty in meeting the specification. Simulation modelling for the test run case also verified that the fractionation sections in the crude atmospheric column were overly sensitive to the internal reflux rates. To compensate for this sensitivity, the crude column had been operated with high top pumparound rates and high internal reflux for naphtha and kerosene fractionation. Through these evaluations, it was determined that the pumparound design had not been optimum since the initial design stage. In addition, the crude feedstock change further aggravated the pumparound capacity. It was necessary to optimize the crude column design, including the pumparound rearrangement at current crude slate conditions, for maximum crude unit capacity and performance.

**Current retrofit design**

Based on the test run simulation results, a new simulation model for the current retrofit was developed. The existing tray performance with simulated traffic predicted that the existing single kerosene draw configuration could not produce the required kerosene yield. The current retrofit target yield required a much larger kerosene side stripper as well. As mentioned earlier, installation of a larger kerosene side stripper was not feasible. To increase the kerosene yield with a minimum mechanical modification scenario, the existing LGO draw was converted to a heavy kerosene draw. In this case, the number of kerosene draws was increased from one to two, while the gas oil draws were reduced from three to two. This retrofit strategy did not require any column nozzle and external piping configuration changes.

With these product layout conversions, the existing LGO and MGO pumparound circuits were converted to new heavy kerosene and new LGO pumparound circuits, respectively. The pumparound balance was optimized between the new LGO and HGO pumparound sections to improve overall capacity as well. The pumparound capacities of the current retrofit design are plotted in blue in Figure 5. These capacities are based on a new higher crude charge rate using new high-performance...
trays and new structured packing, as part of the current retrofit. A recognizable improvement in pumparound balancing is demonstrated in this graph. Process configuration changes per product and pumparound rearrangement are highlighted in Figure 6.

These product and pumparound rearrangements resulted in a lower logarithmic mean temperature difference (LMTD) for the new heavy kerosene and new LGO pumparound circuits compared to previous services. A careful evaluation of the preheat train was required to make sure the new configuration did not result in a lower preheat temperature to the furnace and/or possibly reduced recovery or higher energy consumption. Some modifications to the preheat train and exchangers were completed to optimize the heat recovery at the new conditions. An overall heat balance check, including furnaces, showed the desired feed temperature would be achieved at the current retrofit design condition.

An existing distillation equipment evaluation with simulated traffic showed that the existing trays and HGO pumparound packing were unable to handle the required traffic at the current retrofit rates.
To increase distillation equipment performance, all trays in the crude atmospheric column were replaced with high-performance trays.

One important point when tying simulation design to actual distillation equipment performance involves the effect of internal vapour and liquid distribution and the internal liquid-to-vapour \((L/V)\) ratio in each section of the tower. Figure 7 illustrates the multiple internal vapour and liquid streams in a four-pass tray. Steady-state simulation modelling assumes that the ratios are equal, while in actual operation it is rarely this close. Poorly designed or imbalanced multi-pass trays and/or improper feed arrangements can exacerbate this problem, resulting in lower-than-expected tray efficiencies or, in some cases, a reduced ultimate capacity. Previous references have noted balancing methods for multi-pass trays in order to achieve this \(L/V\) ratio.\(^5\)

The top pumparound return liquid distribution design was addressed during the current retrofit. In particular, four-pass trays were used for most of the pumparound circuits, and the existing top tray downcomers were positioned as two off-centre locations. Liquid must be irrigated to three inlet panels: one centre and two side-positioned inlet panels. In this case, it is very difficult to achieve desired distribution using a conventional distributor, as each inlet needs a specific metered amount of liquid. The new distributor coupled with a balanced tray design must meter this liquid properly to insure the new targets are met.
During a previous turnaround, it was found that the top pumparound trays had lost a significant number of movable valve units from the tray decks. Valve/perforation hole wear and corrosion, which are common problems in this section, were the root cause. To alleviate the problem, the top pumparound active areas were replaced with fixed-valve decks. However, there were performance/fractionation variations after this previous replacement. Petroleum gas and naphtha yield structure and cooler performance varied the top pumparound circulation rates significantly. The liquid and vapour profile from the top to the bottom of the pumparound varied greatly. Detailed tray evaluation at various ranges of operation and crude slate structure showed an excessive tray opening area, causing heavy weeping at the top tray of the pumparound. A review of tray drawings revealed that the same number of holes (same valve open area) was applied for each pumparound tray deck to simplify tray manufacture and reduce cost. For the current retrofit design, each top pumparound tray open area was re-arranged and optimized per simulated traffic. Tray open areas were progressively increased through the section to mitigate weeping. High performance fixed valves were applied to meet the required top pumparound capacity.

The transition section design between fractionation and the LGO pumparound section also had distribution issues. However, space constraints meant it was not a simple matter of designing a feed pipe and transition to balance the tray flows. In this case, the number of passes for the LGO pumparound was changed from four to two, as four-pass trays were unnecessary. This change coupled with the new pumparound return piping alleviated any distribution issues.

The structured packing for the HGO pumparound was replaced with new packing as well. To increase packing capacity, a higher capacity packing was chosen. In this case, a big concern was a possible reduction in heat transfer efficiency, as higher capacity packing will generally result in lower efficiencies. However, careful understanding of the heat transfer coefficient calculations will allow the process designer to meet any duty requirements.

The bottom stripping section was also modified to maximise distillate recovery. Steam stripping trays are operated at low vapour and high liquid traffic. While a high amount of reduced crude is transported through the stripping tray downcomers, only stripped hydrocarbon and stripping steam are included in the vapour phase. The result is that the active area is not a controlling factor in determining stripping section capacity. Oversized open areas over an active area decrease vapour velocity. This low velocity does not generate enough froth for vapour and liquid contact and downgrades stripping efficiency. Weeping at the bottom stripping trays is a common problem in this section, especially as the vapour traffic at the bottom stripping tray contains only the stripping steam. The original stripping section consisted of five four-pass trays. Although five trays were assigned to this section, it was found that the last stripping tray was designed as a blind tray. The existing four-pass tray did not provide adequate steam distribution across the active panels and caused vapour channelling. This cross channelling can downgrade stripping efficiency as well. Increased stripping steam rates were used to compensate for the efficiency loss at the penalty of increased condenser load.
For the new tray design, the flow path quantity was reduced from four to two. New two-pass trays with optimum downcomer design would be able to handle the required flow rates, and many of the distribution issues would easily be solved. The average flow path of the liquid on each tray was increased as well, which helped enhance tray efficiency. The tray open area was optimized to maintain good vapour velocity. Special active area modifications also helped maintain the plug flow regime in the liquid phase. Cross channelling was corrected in the new tray design. The new light kerosene stripper trays were also modified with similar design philosophies.

**Startup**

The crude unit was shut down and modified according to the current retrofit design. The startup procedures of the crude distillation unit were reviewed and updated to match the current modifications. The effect of the lower pressure drop through the column and high-performance trays needed
to be evaluated for successful unit startup and operation. Every aspect of the startup was considered to avoid undesired delays that might impact the refiner's economics.

High-performance trays in this crude atmospheric column utilise a dynamic downcomer seal design. In this advanced design, the downcomer clearance is greater than the outlet weir height. The downcomer sealing is easily maintained with adequate liquid flow to prevent vapour from bypassing up the downcomer. However, extremely low liquid and vapour rates (below normal minimum operating conditions) may be encountered during initial startup. Thus, the downcomer seal may be lost, resulting in poor fractionation and other operating difficulties. To eliminate potential downcomer unsealing problems, the initial crude charge rate and the pumparound rates at startup were increased from previous startup initial charge rates, and the refinery operations team was trained in how to avoid such problems.

Light/heavy kerosene and LGO draw temperatures were also changed per pumparound rearrangement. The temperature profile change increased the difficulty in establishing heat and material balances during startup. Before increasing the initial charge rate to target capacity, all operating parameters were monitored and reviewed sufficiently after establishing heat and material balances at the initial charge rate.

**Post current retrofit performance**

This crude unit was successfully revamped and its target capacity was met. Table 1 summarizes pre and post current retrofit operating data. Two sets of test run data are shown to check unit performance. Test run 1 and 2 indicate operating data at kerosene- and dieselrich crude slates, respectively. Overall unit capacity has been expanded and kerosene-rich crude slates are processed without any limitation. Although the number of diesel pumparound circuits was reduced, the crude unit produces much higher diesel yields.

Column fractionation efficiencies are substantially improved. Fractionation efficiencies among products are enhanced at higher distillate production rates, lower stripping steam injection rates and lower furnace outlet temperature. The final processed crudes are actually heavier feedstock containing more atmospheric residue boiling range material. Separation between diesel and reduced crude is improved and the reduced crude 5% distillation temperature is increased, indicating improved diesel recovery. Pressure drop is maintained or reduced at higher product yields. Lower flash zone pressures lift more distillates at the same furnace outlet temperature or reduce the furnace outlet temperature at the same distillates. This pressure drop improvement also help to minimise the energy consumption of the crude unit. Stripping steam savings help the refiner's economics too.
References

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