Improving crude vacuum unit performance

When simulating or designing an unconventional heavy oil/bitumen vacuum crude unit, the sharing of operating data on cracked gas make, stripping section performance and indirect entrainment can help ensure designers make the right design choices

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The refining industry is becoming more experienced at operating vacuum units that process unconventional heavy oil/bitumen-derived crudes. New vacuum units are being planned, and the knowledge gained from existing operations could improve the economics of these projects by incorporating the nuances in processing these crudes to create robust designs that represent actual operation.

This article focuses on sharing data specifically from unconventional heavy crude vacuum units operating in wet mode (stripping and velocity steam)[1] to provide some insight into using a proven vacuum distillation tower simulation topology[2] with heavy oil/bitumen upgrader feeds.

When simulating or designing a heavy oil/bitumen upgrader vacuum column, the following design factors need to be incorporated, in order of importance:

1 Crude characterisation[3,4]
2 Thermodynamic choice[3,4]
3 Simulation topology (non-equilibrium).[2]

Each subsequent design factor cannot compensate for poor crude characterisation or thermodynamics choices. Assuming the heavy oil/bitumen crude has been characterised appropriately for the higher boiling point components (eg, using both ASTM 2887 and HTSD),[5] and the representative thermodynamic package is chosen (eg, variation of Peng-Robinson, Grayson-Streed, Esso Tubular, BK10), the focus for the vacuum column design shifts to simulation development. Table 1 illustrates the use of different default thermodynamic equations in a vacuum column, and the difference can be significant. The thermodynamic package must be appropriately set before the simulation topology and any simulation enhancements can be considered.

Figure 1 shows a proven vacuum column simulation topology[2] that addresses the realities of the physical system built. The bottoms of the atmospheric crude column is heated

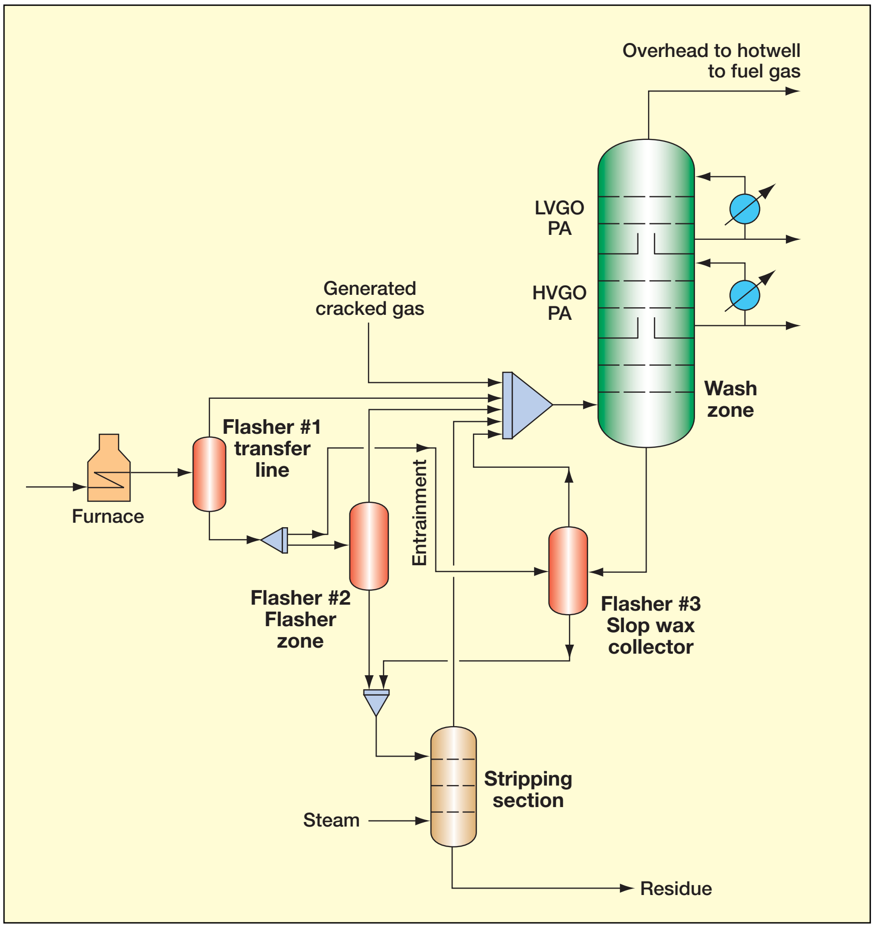

Figure 1 *Proven vacuum column simulation topology to represent non-equilibrium tendency in feed to vacuum column.[2] Experience factors for bitumen-derived crude for cracked gas, entrainment and the stripping section should be provided to adequately represent actual operation*

(partially vapourised) in a vacuum heater to provide the necessary energy to separate the higher boiling components at a reduced pressure in the vacuum column. In the simulation, the column is divided into two main sections (stripping and above the flash zone). The transfer line is partitioned into separate vapour and liquid streams to address the non-equilibrium situation, and various flashes address entrainment and the specifics of the flash zone and slop wax collector tray. It has been shown that the predictions on HVGO yield and the

Comparison of different default thermodynamic packages on representation of vacuum column

Thermodynamic package	Vapourisation at flash zone TP, wt%
Peng-Robinson	35.0
Grayson-Streed	32.8
Esso Tubular	31.4
BK10	29.3

Table 1

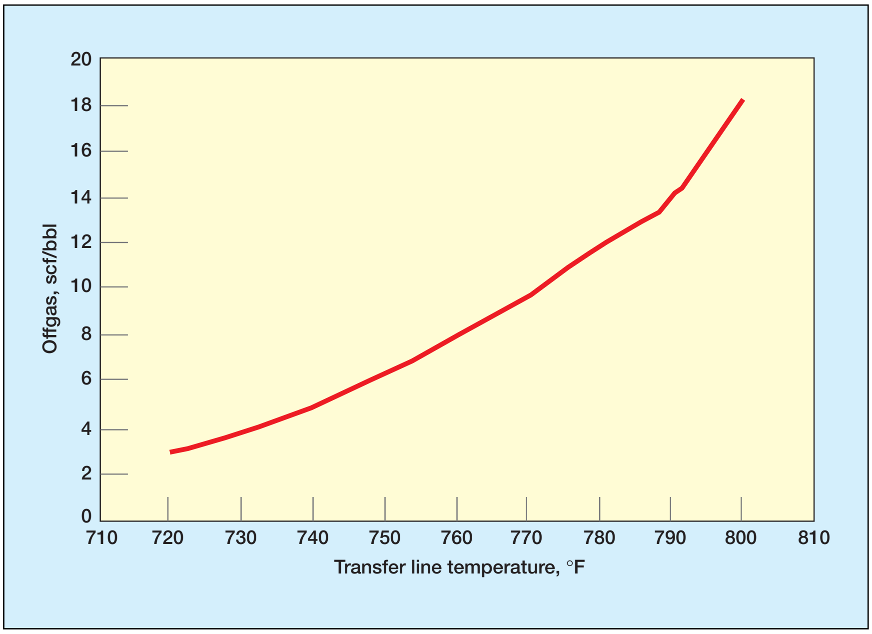

Figure 2 *Graphical representation of Lieberman relationship; measured plant variables, transfer line temperature and off-gas-to-crude flow ratio*

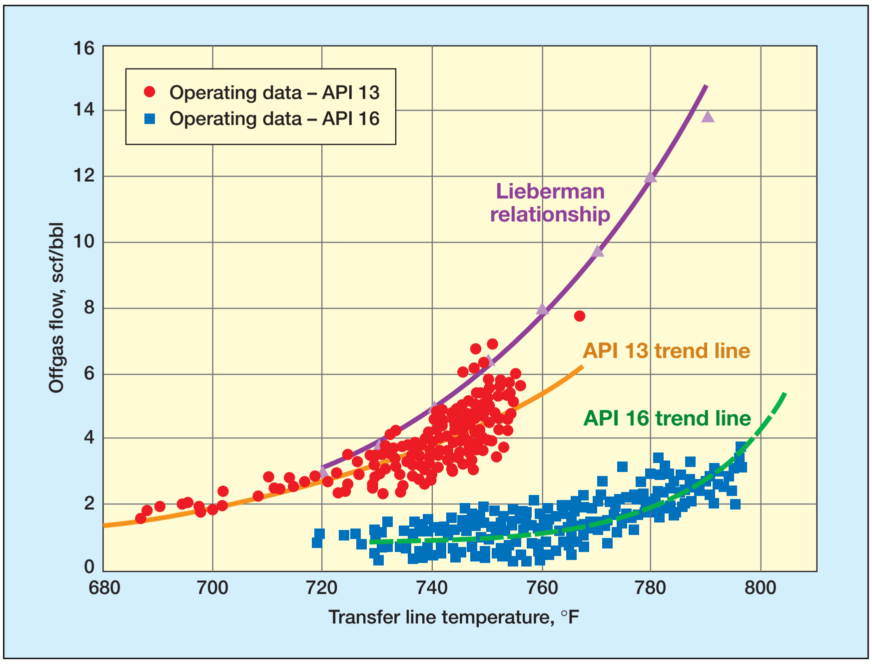

Figure 3 *Addition of API 13 and 16 data sets to the transfer line temperature vs off-gas-to-crude flow ratio relationship. Trend lines are provided for each data set*

liquid rate to the top of the wash section from Figure 1's topology match up well with the plant's data.[2,3,6]

After reviewing operating data from various units, Figure 1's simulation topology has been used to enhance the representation of a bitumen-based feed vacuum unit by capturing the thermal and variable stability characteristics of the crude. The cracked gas generated, the entrainment formed and the performance of the stripping section should be critically evaluated to ensure these factors represent the bitumen's characteristics.

Cracked gas make

The operational and thus economic impact of underestimating crude cracking in the vacuum heater is large due to increased light hydrocarbon molecules, which can reduce the effectiveness of the vacuum ejector system, and increased coke particle generation, which can reduce column run length and throughput capacity,[7] and result in a reduced maximum film temperature and a low residence time. These heater design guidelines are a function of the crude being processed, and typically the impact of the heater design is not fully included in the simulation.

Figure 2 shows a published relationship (Lieberman) that uses readily available measured plant data that relate the transfer line temperature to the amount of off-gas (scfd) leaving the vacuum unit[8] (assumed downstream of the vacuum hot well) as a ratio to the crude flow (bpd) to the unit. Basically, the trend is that as the heater's temperature increases, the quantity of off-gas per crude feed increases as well. This relationship is only as good as the field measurements, but provides a tangible appreciation of the degree of cracked gas generated from an unknown heater design. This off-gas value is lumped, consisting of air ingress, dissolved hydrocarbons in the feed, residual water and cracked gas. From the data gathered, a reasonable assertion appeared to be that the cracked gas comprised the majority of the off-gas and was the prominent contributor to the increase in off-gas flow when the heater's temperature increased.

Figure 3 shows two data sets taken from vacuum units processing crudes with vacuum feed APIs of 13 and 16. Both data sets support the Lieberman relationship trend that as the transfer line temperature increases, the off-gas flow-to-crude feed ratio increases as well. The API 13 data set seems to match the Lieberman relationship well, while the API 16 data set seems to generate far less cracked gas. Trend lines were added to Figure 3 for each data set to reflect the Lieberman relationship representation.

Figure 4 includes trended data from vacuum units processing more heavy (API 6–10) unconventional crude. Again, the relationship where the amount of off-gas flow increases as the transfer-line temperature increases (from increased heater firing) is reflected in these data sets. In general, vacuum units processing heavier crudes will operate at lower heater outlet temperatures than lighter crudes, primarily due to the tendency for the heavier crudes to be more unstable at higher temperatures. The instability translates to increased coke generation and light hydrocarbon formation. Also, obviously as the API decreases, the degree of off-gas increases. However, many vacuum unit designs do not reflect this situation. For example, at a temperature of 700°F, the API 13 crude tends to exhibit an off-gas-to-crude flow of 2–3 scf/bbl, while for the API 10 crude (eg, Cold Lake) the scf/bbl would be 6–7 (ie, more than double).

This type of simplified relationship between API (primarily bitumen derived) and off-gas flow (cracked gas make) has implications on vacuum column unit design. Assuming a desire to operate the vacuum unit at as low a pressure as possible (to maximise HVGO product yield), the overhead vacuum ejector design/size and the heat-transfer capabilities of the quench/pumparound zones will be different if the data in Figure 4 is used rather than the data available in literature.[8]

Figure 5 shows one operating example

and one redesign example (not in operation yet). Point A reflects a design point now in operation for an unconventional crude with a feed API 10, where the actual off-gas flow was significantly more than expected for the designed heater outlet temperature and HVGO yield. The vacuum ejector system was overwhelmed, and the heater outlet temperature was reduced by approximately 35°F (point B), thereby reducing the HVGO yield significantly. It appears that the design point A for the off-gas flow (cracked gas make) was based on the cracking characteristics of a more conventional crude. Point B' is a suggested design point, using the benefits of an operating experience database. Understanding and applying the specific crude characteristics (crude characterisation and validating with similar data points) is crucial if a design is to operate as intended.

The second case shown in Figure 5 is still in design mode, with point C representing the initial design case. After sharing any operating experience with the process designer, point C was modified to point D. Basically, the amount of cracked gas generated was increased, based on an extrapolation of the shared operating data. The concern with this approach is that the high heater outer temperature is still desired. The chance of accelerated coking in the heater at these high temperatures for unconventional crudes is high. Point D' is suggested, incorporating an increased cracked gas and a reduced outlet heater temperature.

A few generalisations can be drawn from Figure 5. For both the API 6 and 10 crude trend lines, there is a temperature (approximately 710°F for API 10 and 700°F for API 6) at which the off-gas flow (heater cracked gas make) accelerates. Each crude should be inspected on a case-by-case basis, but from the data in Figure 5 and similar comments from experts, heater outlet temperatures for heavy crude with instability tendencies and asphaltenes (eg, Canadian Bitumen) should be designed not to exceed a maximum of 710–715°F for API 10 and 700°F for API 6.

The design and subsequent operation of the vacuum heater is crucial in the performance of the vacuum column. Along with heat flux (peak and average), residence time should be economically minimised in the design phase. Oversizing the vacuum heater for potential future feed increases will invariably impact the residence time, increasing the time the crude stays in the heater to coke and/or crack.

Figure 6 shows an example where a vacuum unit was run at reduced rates for an extended period of time (six months) due to a lack of feed. The residence time of the crude in the vacuum heater increased dramatically, while the bulk operating temperature was below the design temperatures specified. The impact of the peak oil film temperature was not factored into this evaluation, but is a very important design/operating parameter when dealing with oil with thermal stability issues. Based on the data provided and the assertion that since the operating temperature was below design temperature the peak oil temperature was likely not near its limit, the oil residence time should be considered a large factor in cracked gas make in the vacuum heater. The implication is that oversizing a vacuum heater for design margin or future debottlenecking scenarios will impact the performance of the vacuum unit (coking in the vacuum heater to reduce run length and/or reduced throughput from an overwhelmed vacuum overhead ejector).

From Figure 6, the cracked gas make per crude barrel produced was double the full design rates. In addition, the design case off-gas flow underspecified the amount of cracked gas make, resulting in the vacuum ejector being overwhelmed with only 60–65% of design crude flows. After a maintenance turnaround, the rates were increased close to design rates, with a subsequent reduction in the

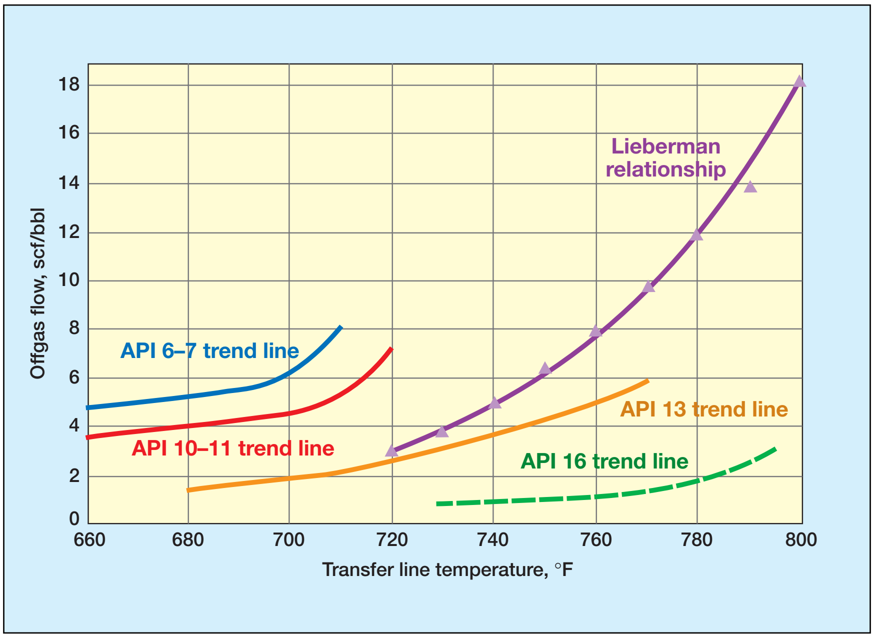

Figure 4 *Addition of heavier unconventional crude data sets to the transfer line to off-gas flow-to-crude flow ratio relationship. From the data illustrated, as the API decreases (heavier crude), the degree of cracked gas (translated to off-gas) increases*

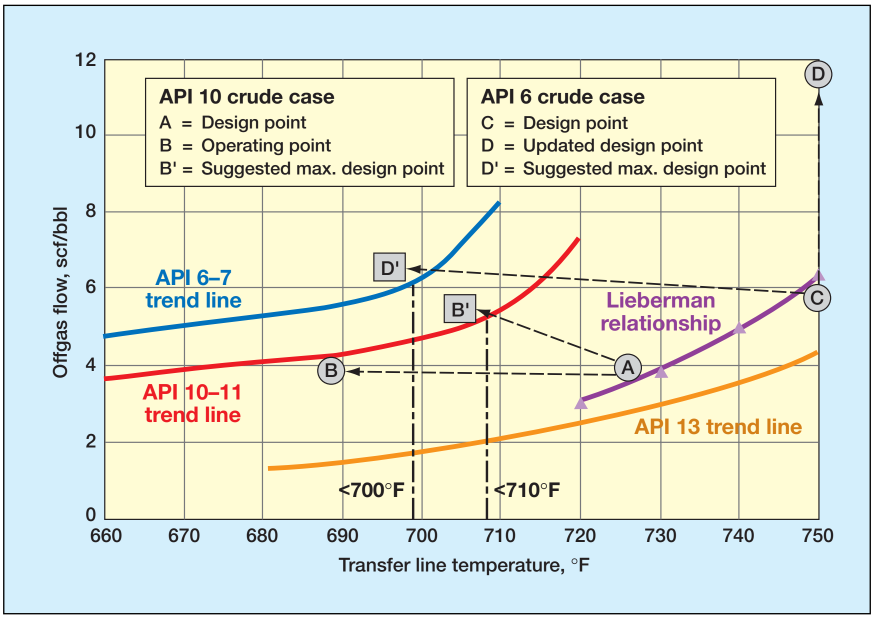

Figure 5 *Operating case: point A was a design point for an API 10 unconventional crude vacuum unit. The unit operated at point B, a lower heater outlet/transfer line temperature. Point B' is a possible design point. Design case: point C was a design point for an API 6 unconventional crude vacuum unit. The unit is now desired for point D, while point D' is suggested as a design point (reduced heater design temperature)*

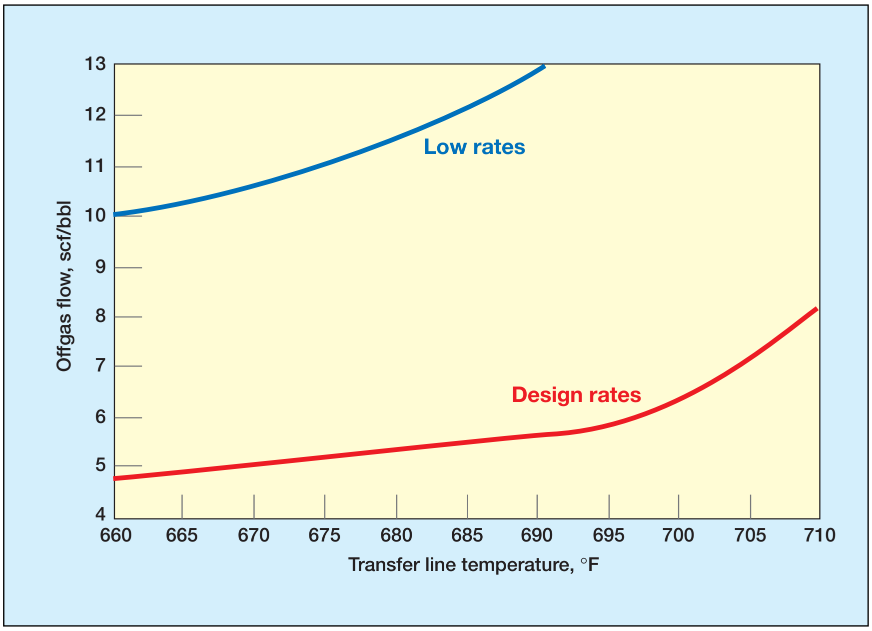

***Figure 6** Cracked gas make for an API 6–7 unconventional crude vacuum unit, comparing low feed rates (approximately 60–65% of design rates) to design feed rates. The off-gas flow per barrel of crude produced was nearly double for the low flow rates*

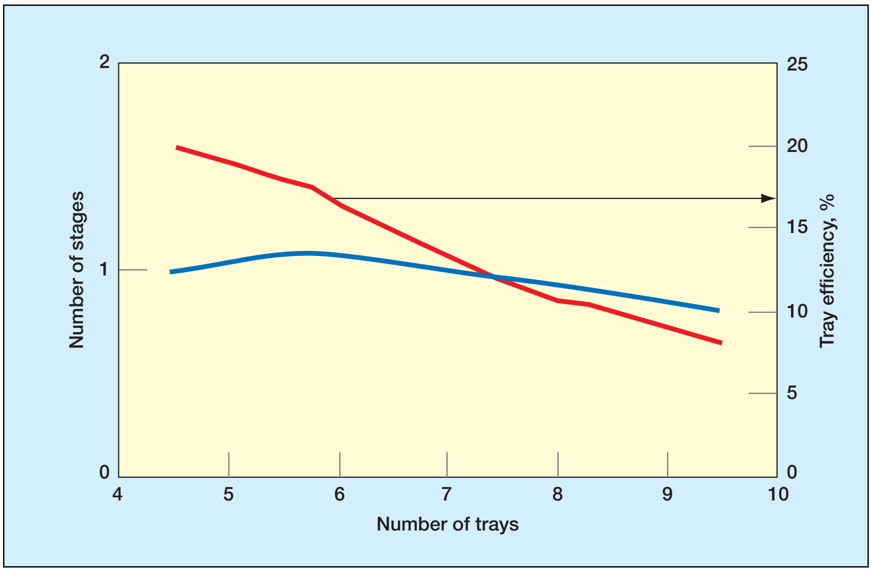

***Figure 7** An observed set of tray separation stages for different tray counts in operating vacuum units. The tray count appears to be insensitive to the actual number of stages (approximately one), represented in a reduced tray efficiency*

off-gas flow per barrel. A plausible hypothesis is that the oil residence time reduced below a critical point, and thus the time to coke/crack a large part of the crude was reduced, generating a more expected off-gas flow.

Stripping section (residue stripping)

The increased recovery of VGO due to stripping steam is related to the operating pressure in this section. Steam stripping lowers the hydrocarbon partial pressure to allow the material to boil at a lower temperature. The pressure drop is generated by the internals. The operating tray pressure drop (0.07–0.1 psi/tray) is a small percentage of the operating pressure, but in vacuum service the tray pressure drop constitutes a large portion of the overall section pressure drop. In this stripping service, there is typically a rapid approach to equilibrium occurring within (primarily) one to two stages.[10] In the simulation, the appropriate tray efficiency and expected pressure drop generated are input into the simulation as per Figure 1 (a separate column). Figure 6 provides data from ten operating units,[3] illustrating the observed staged count from matching plant data to a representative simulation. For actual tray counts between five and ten, the simulated stage count is one. A simple way to explain this observation is that the pressure drop added from the increase in trays offsets the added separation provided by the additional trays. The stripping factor (KV/L; K = equilibrium constant, V= vapour flow, L= liquid flow) reflects this relationship, with the equilibrium constant represented as P_{VHC}/P_T (P_{vHC} = hydrocarbon vapour pressure, P_T= total pressure). So, as P_T increases from the added tray pressure drop, the stripping efficiency reduces. As shown in Figure 7, it is proposed that as the number of trays is increased in the stripping section, the individual tray efficiency decreases, resulting in a simulated stage efficiency of one. This relationship, or specifying one simulated stage, should be incorporated into the unconventional crude vacuum column design.

Additionally, the thermodynamic variable, water activity coefficient, γ_{H2O}, in the following Equation 1 can be adjusted in the simulation (based on the type of unconventional crude and operation conditions) to improve the realistic representation of the steam stripping section:

$$P = P_{V(HC)}\chi_{HC} + P_{v(H20)}\chi_{H20}\gamma_{H20} \qquad \text{Eq 1}$$

The variable P represents the pressure of the stripping section, and the first term $P_{v(HC)}x_{HC}$ ($P_{v(HC)}$ = hydrocarbon vapour pressure, x_{HC} = liquid composition of hydrocarbon) is the hydrocarbon contributor, and the second term $P_{vH20}X_{H2O}\gamma_{H2O}$ is the water contributor to the total pressure in the stripping section.

To address the sensitive nature of the increased pressure drop in the stripping section, and the challenge in designing trays (large change in vapour load from top to bottom tray) to maximise individual tray efficiency, an open-area grid (not corrugated sheet variety) has been used in a couple of unconventional crude vacuum column stripping sections to increase the overall HVGO yield of the unit. The real grid has a high open area and is robustly constructed, thus having good fouling mitigation and durability characteristics. The wetting of the grid to prevent premature coking is high due to the reduced diameter in the section and the high liquid-to-vapour ratio in this section.

Table 2 summarises the performance comparison between a five-trayed stripping section and equivalent grid. Compared to five trays that will generate a pressure drop of 25–40 mmHg, one equivalent separation stage of grid will generate only 0.5–0.6 mmHg of pressure drop. This difference in pressure drop and the separation characteristics of the grid vs trays can provide an increase in HVGO yield of 2–3% of total vacuum unit feed.[3] For a 50 000 bpd vacuum unit feed, the increased HVGO production would be 1000–1500 bpd. The trade-off to the increased HVGO production is the increased capital expenditure from the internals and longer stripping section, and the requirement for good liquid and vapour distribution for the grid.

Entrainment

The amount of heavy liquid particles (entrainment) slated for the vacuum tower bottoms present in the flash zone vapour (impacting HVGO quality) is a function of the geometry of the transfer line and performance of the flash zone (inlet nozzle and feed device). Setting the appropriate entrainment value will improve the accuracy of the economic sensitivity analysis for different transfer line designs, inlet feed devices and wash bed configurations. However, this article focuses on sharing operating data to help with developing a representative simulation.

Since there are no direct field measurements for entrainment (calculations can be performed with quench and slop wax flow measurements), operating data evaluating the quality of the HVGO product can be used as an indirect measure of the level of entrainment. Entrainment numbers should include detailed hydrodynamic evaluation of the transfer line and flash zone geometry. Guidelines are available for specific unconventional crudes and geometries that can be input into the simulation to improve its realistic representation. Figure 8 shows a typical performance evaluation of two styles of radial inlet feed device: vane and vapour horn.

The choice of an inlet feed device can provide a tangible performance difference to a vacuum column. An industrial revamp converted a vane-style inlet device to a proprietary enhanced vapour horn to take advantage of the reduced entrainment from the vapour horn design. The range of entrainment values for unconventional crude can be 2–3 wt% of the liquid in the outlet of the vacuum heater. Transfer line and flash zone liquid entrainment contains material slated for the vacuum tower bottoms, which contains significant contaminants (metals such as vanadium for the downstream catalytic conversion units).

A properly designed enhanced vapour horn can reduce the entrainment by 25–30% over a standard vapour horn or vane-style device, thereby allowing an increased throughput through the unit. The enhanced vapour horn setup takes advantage of downward momentum (Stokes' Law) to reduce entrained liquid and the vanes and baffles to improve vapour distribution for the mass transfer in the wash bed. In the revamp of a vane-style feed inlet device to an enhanced vapour horn, shown in Figure 8, the flow rate was increased by 15% while maintaining the HVGO product quality. The calculated entrainment rate at the post-revamp rates was also lower than the pre-revamp rates with the standard vane-style device.

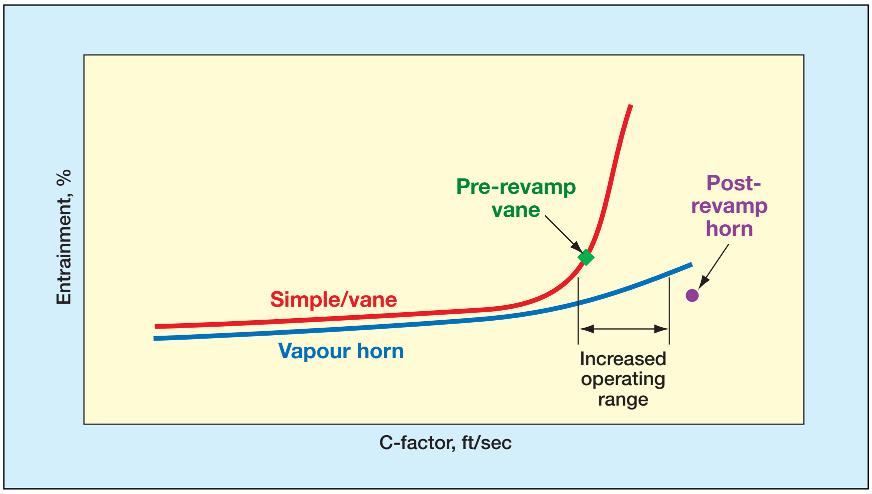

Figure 8 *CFD analysis validating actual operating points pre- and post-revamp of a vacuum tower feed inlet device. An enhanced vapour horn replaced an even flow inlet feed device, allowing an increase in unit feed rate while maintaining the HVGO product specification (by decreasing entrainment generated)*

Comparison of trays and grid in the stripping section of a vacuum column

	Trays	Grid
Internals specification	5 fixed valves 27 in tray spacing (11 ft 3 in height)	Liquid distributor 14 ft of grid
Pressure drop per unit	5–8 mmHg/tray	0.5–0.6 mmHg/m
Total pressure drop in section	25–40 mmHg	2–2.6 mmHg
Yield improvement	Base	2–3%

Table 2

Operating data validated by CFD analysis, in Figure 8, illustrates the performance differences provided by the choice of inlet feed device. The equipment characteristics of the specific inlet feed device should be input into the simulation by factoring the subsequent entrainment expected due to transfer line and inlet feed device design.

Conclusions

Operating data have been gathered and shared to give designers some insight when designing unconventional heavy oil/bitumen vacuum crude units, specifically data for cracked gas make, stripping section performance and indirect entrainment information in the form of HVGO product quality. As corroborated in literature,[5,7,9] unconventional crudes need appropriate design considerations to be applied to the vacuum unit design simulation. Designers should track down all relevant data to improve their chances of realistically representing the expected operating situation from the design choices made. The data provided in this article can be used as a validation point for vacuum column designs with unconventional crudes.

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