January 2006
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Process Developments

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Consider a practical approach to vacuum unit revamps

Here are some major operating issues to evaluate in the front-end design

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Vacuum distillation operations are quite effective and can upgrade the bottoms of the crude unit into higher-valued products and blending streams. Nevertheless, refiners are exploring all opportunities to maximize capacity while minimizing equipment modifications. Revamping vacuum towers is key for upgrading the total refinery throughput. Retrofitting the vacuum tower poses many challenges; however, the benefits from such projects outweigh the negatives. The following examples demonstrate opportunities to increase performance of an existing vacuum tower.

Vacuum distillation has benefits. Vacuum distillation is a key refining unit operation positioned downstream of atmospheric distillation towers. Topped crude and heavy oils are processed at sub-atmospheric conditions to recover valuable gasoils. Vacuum distillation is used to vaporize heavy oil at low temperatures that avoid unacceptable rates of coking and cracking.

Most commercial vacuum distillation towers recover gasoils for downstream cracking units, while others produce lubricants. Also, vacuum towers are used to produce lube-grade gasoils for further processing in lubricant production units. Vacuum tower bottoms are usually sent to the resid upgrading/ cracking facilities such as coker, visbreaker and FCC units.

Vacuum tower retrofit. Process evaluation of vacuum tower expansion is a complex task; it requires satisfying several variables including operating at the optimum temperature and pressure, designing for acceptable jet flooding, meeting products specifications and minimizing vessel modifications. Increasing the feed usually requires an equivalent increase in the vapor/ liquid traffic and pumparound condensing duty; accordingly, three major limitations should be addressed in a vacuum tower revamp: hydraulic capacity, mass transfer efficiency and heat transfer capacity.

Packing selection at the maximum capacity. A significant increase for the charge rate to a vacuum tower may push the vessel to the maximum hydraulic and heat transfer limit. To meet all operating requirements, using one packing type in each of the light vacuum gasoil (LVGO), heavy vacuum gasoil (HVGO) and wash sections may not be feasible. High vapor/ liquid traffic requires high-capacity packing that may not provide the best surface area for heat and mass-transfer. **Result:** The packing height will not fit the existing tower. To overcome this obstacle, a combined (corrugated and grid) packing bed is installed in each section as shown in Fig. 2. In each section, the top packing layers are corrugated-structure packing that are suitable for maximizing surface area, while the bottom packing layers are grid-structure packing, which is suitable for maximizing hydraulic capacity.

This configuration (Fig. 2) has the advantage of lower packing height than that obtained from grid-structured packing bed and of more robust design (lower jet flooding) than that obtained from corrugated-structured packing bed.

Role of pressure and temperature. Two important factors that conceptually define throughput and product rates of distillation towers are the flash-zone operating temperature and pressure. These two factors determine the fraction of feed vaporized, and, therefore, the maximum overhead and side-product rates that could be recovered. The operating pressure is set by two factors: vacuum system capacity and pressure drop across the tower. The pressure drop across the tower is governed by the tower internals, vapor/ liquid traffic, vapor/ liquid properties and hydraulic limit of the tower.

Factors that define maximum attainable temperature are typically the fired heater/ preheat train capacity and temperature at which the coking rate in the fired heater is unacceptable. Also, temperature and pressure conditions are inter-related. For a constant vapor fraction, higher operating pressure at the flash zone requires increasing the flash zone temperature.

Tower flooding and entrainment. The parameter that determines the maximum hydraulic capacity of revamped towers is jet flooding. A maximum jet flooding value of 80 – 85% is considered acceptable for retrofits. However, another overlooked parameter is the liquid entrainment level, especially at the feed nozzle and P/A spray distributors. Entrainment level has several contributors such as vapor distribution, droplet size, droplet physical properties and vapor velocity. A useful parameter to determine the entrainment level is the *C* -factor (C_f *)*, which is a velocity criteria typically used to describe distillation vapor traffic.

$$C_f = v_s \sqrt{\frac{\rho_v}{\rho_l - \rho_v}}$$

where:

v_s is the superficial velocity

r_v is the vapor density

r_l is the liquid density.

Liquid entrainment at the feed causes excessive amounts of VTB droplets to travel up the column to the wash zone, vaporizing colder wash oil, leading to dry out and coking of the wash section. The entrained liquid appears in the slop-wax stream, giving a misleading indication that the wash section is properly handling enough liquid to avoid coking. Eventually, undesired heavies, metals and contaminants that should have been washed appear in the HVGO product.

The same issue is also observed in pumparound spray distributors where entrained liquid droplets travel upward, harming heat transfer and contaminating VGO products.

Remember: A safe *C*-factor value is also a function of proper vapor distribution. In one case, a *C* -factor of 0.46 ft/s was achieved without excessive entrainment when a suitable vapor distribution device was used.[1] As a general rule for revamps, given that adequate precautions are taken for sufficient vapor distribution (such as radial vapor horn device), a safe *C* -factor value to operate at is 0.40 ft/s.

In an actual case study, *C* -factor at proposed design conditions was found to be more than 0.50 ft/s and the following measures to reduce the *C* -factor were taken using the help of simulation:

- Vapor fraction at the feed to the vacuum tower was set as a specification in order to maintain side products recovery (see previous discussion regarding role of pressure and temperature).
- The operating pressure was increased to raise vapor density, thus decreasing superficial velocity and *C* -factor.

However increasing pressure at constant vapor fraction resulted in an increase in flash zone temperature. Higher furnace outlet temperature was limited by preheat train/ fired heater capacity, coking and cracking considerations. To address these limitations, the following actions were considered:

- Available vacuum feed heater duty based on allowed over-design margin was identified.
- Field survey data and in-house guidelines were reviewed to determine historically acceptable operating temperature for which coking was not an issue.
- The increase in cracking rate due to the higher furnace outlet temperature was estimated. The design of the third steam ejector, which mainly handled a non-condensible load to the vacuum system, was revised.

Pressure drop across the transfer line was recalculated to determine the true furnace outlet pressure and temperature, which are important for furnace velocity design.

Properly design inlet devices. Achieving a lower *C* -factor does not guarantee that excessive entrainment is reduced to acceptable levels. Adequate vapor distribution is important to ensure consistent *C* -factor at all points across the tower diameter. In grass roots projects, adequate vapor distribution at the charge nozzle is not critical since the *C* -factor is usually low, and the vapor adequately redistributes in the allotted spacing between the charge nozzle and bottom of the wash section. Meanwhile, in revamp projects, the *C* -factor is driven higher and the available tower spacing is inadequate.

At the charge nozzle, the revamp limitations require using a specialized vapor-distribution device such as a radial vapor horn, tangential vapor horn or schoepentoter. To enhance equal vapor distribution at the feed and across the tower diameter, a radial horn devise with cut-off vanes is recommended over schoepentoter and tangential vapor horn devices.

This same issue is also applicable for the spray distributors located in LVGO, HVGO and wash sections. Spray distributors with wide-angle spraying are prone to liquid entrainment, especially at high *C* -factor values; these measures should be addressed:

- Narrow spraying angles of 90° or 105° with 200% spray coverage should be selected.
- Entrainment rates should be estimated[2] and incorporated in the simulation or set as an over-design for each spray distributor.

Changing product-to-product ratios. In vacuum tower revamps, product specifications may require different boiling-point cuts compared to what is historically processed, resulting in different product-to-product ratios. Consider a typical vacuum tower that consists of LVGO, HVGO and wash sections as shown in Fig. 1. The project goal is retrofitting the tower to recover lube-grade gasoils (typical HVGO to LVGO ratio of about 1:1) instead of the pre-revamp cracking-grade gasoil (typical HVGO to LVGO ratio of 5:1). The results from such significant changes are:

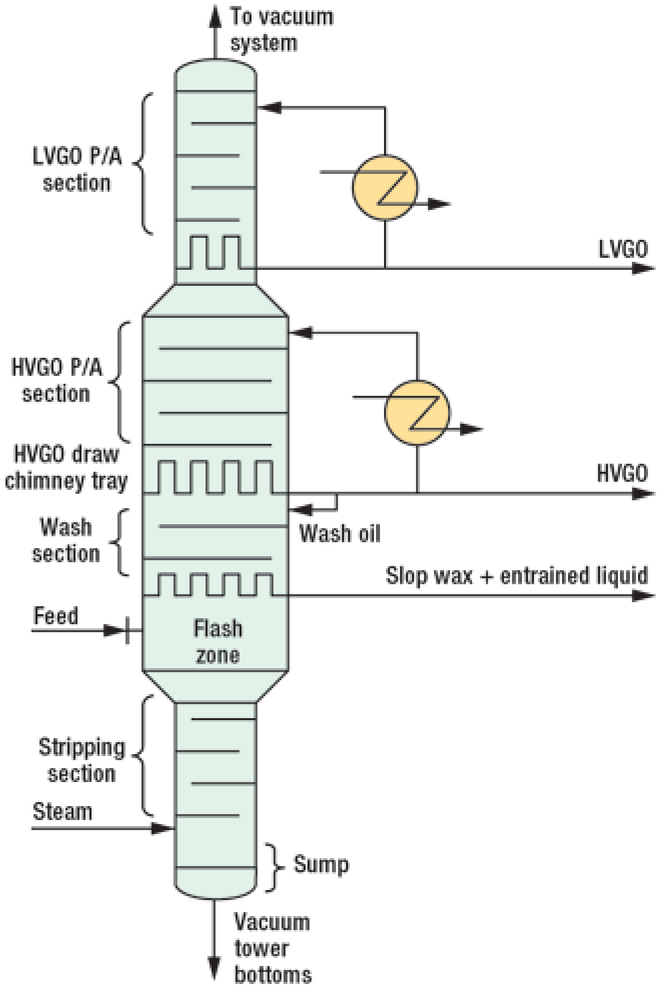

Fig. 1 Trayed vacuum tower schematic.

- Since the LVGO section diameter is typically smaller than the HVGO section, replacing the LVGO section to provide a larger diameter may be required (Fig. 2). **Remember:** Diameters of vacuum tower sections are governed by the original design vapor/ liquid traffic that is largely defined by original charge rate and product-to-product ratios.
- Higher LVGO pumparound duty will be needed to condense the significant increase in vapor/ liquid load in the LVGO section. If the scale of change is significant, replacing or modifying the piping, pumps and heat exchangers may be required.
- Re-evaluating the mechanical vessel integrity will be required since the proposed change will result in higher operating temperatures in the LVGO and HVGO sections; a stress analysis on the tower and associated nozzles should be done.
- Due to higher operating temperatures of LVGO and HVGO sections, the draw and pumparound piping located before the coolers may require upgrading to conform to metallurgy requirements.
- To meet LVGO light-ends lube-grade specifications, significant changes to the hydrocarbon load to the vacuum ejector system may be necessary.

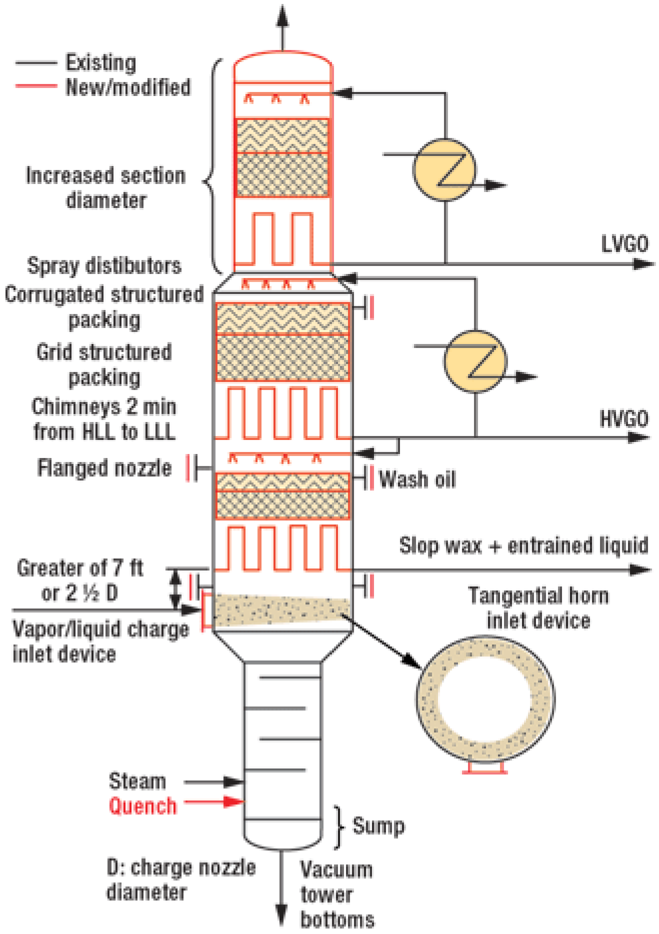

Fig. 2 Schematic of retrofitted vacuum tower. Key revamp areas include space limitation issues, vapor distribution and hydraulic limits for the unit.

Tower spacing. As vacuum towers are pushed to the hydraulic limit, new internals may not fit existing limited tower spacing. Factors that contribute to limited tower spacing are:

- Using low heat and mass transfer packing to address hydraulic requirements
- Increasing heat and mass transfer requirement due to increased throughput and new design specs
- Providing adequate spacing to accommodate pump-around spray and trough distributors
- Allowing satisfactory spacing between the charge nozzle and the bottom of the wash section as shown in Fig. 2
- Designing for sufficient residence time on chimneys.

Minor changes that may result because of tower space limitations include:

- Adding new draw, pumparound and instrumentation nozzles.
- Flanging of existing nozzles that interfere with new internals.
- Removing of welded supporting rings that interfere with new internals.
- Providing new manholes to access the new internals.

The major impact would be to extend the tower height; this is a major cost escalation item if not identified at the appropriate project stage, and may result in engineering rework:

- Piping layout, isometrics and stress analysis
- Equipment elevations such as the vacuum ejector system
- Pump hydraulics
- Mechanical and civil structure elevation and integrity
- Vessel mechanical integrity and stress analysis.

Tower internal vendors often do not investigate such issues at the front-end stage since they prefer to do the detailed work after the award. It is the design engineer's responsibility to verify that the vendors' recommendation will fit the tower. Verbal or written confirmation by vendors is not enough. The process/ mechanical engineer should draw a schematic of the tower with existing and new internals and nozzles to identify any hidden issues at early stages of the project.

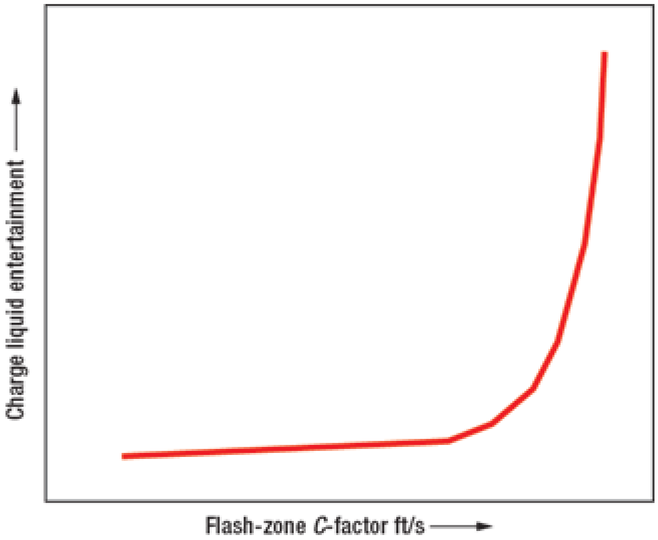

Fig. 3 Relationship of the *C* -factor and charge nozzle entrainment.

Vacuum system retrofit. A vacuum ejector system or a vacuum pump is used to generate vacuum in towers. Vacuum level at the top of the distillation tower is a function of vacuum system capacity, overhead gas rate, overhead gas temperature, required suction pressure and noncondensibles load.

The noncondensibles rate is critical for sizing vacuum systems, especially the last stage ejector of a multi-stage system, where upstream inter-condensers should have removed most of the condensibles load. Underestimating the noncondensibles may cause under-sizing the steam ejectors, nonstable operation and nonfunctioning vacuum system.

Noncondensibles are usually sourced to four areas:

- Cracking the process fluid at elevated temperatures in the fired heater, vacuum tower sump and vacuum tower trays
- Leakage of air into the vacuum tower and vacuum system
- Injecting inert gas to the vacuum system for pressure-control purpose
- Inadequate removal of light components in upstream operations.

To estimate noncondensibles, published correlations and rules of thumb are typically used. To ensure that these techniques are conservative, a pressure profile of the existing vacuum system should be constructed. Since the last stage ejector usually handles noncondensibles, the rate of noncondensibles can be estimated using the last-stage ejector suction pressure and loading curve. The calculated value should then be compared to that predicted by noncondensible estimation techniques.

Also, apply these techniques to reduce the noncondensibles load:

- Quench the vacuum tower sump with colder oil/ fluid
- Minimize tower sump residence time and slop wax draw residence time
- Minimize vacuum heater temperature by decreasing the flash zone pressure, given that the *C* -factor is maintained within acceptable levels
- Apply furnace coking reduction techniques such as adding steam to reduce cracking. **Note:** Adding steam to the fired heater reduces coking/ cracking but increases steam load to the vacuum system. This may be acceptable if the vacuum system components handling the condensibles can tolerate the additional steam load while other components handling the noncondensibles cannot tolerate an increase in cracked material load.

Vacuum furnace and transfer line retrofit. Often, vacuum distillation is preceded with a vacuum furnace and a transfer line. Increasing the vacuum tower throughput involves evaluating the vacuum furnace for hydraulic and thermal capacity. Thus, the vacuum furnace and transfer line are considered part of the vacuum tower revamp.

Transfer line stress analysis. Performing stress analysis on the transfer line at upset conditions should be done at an early stage to allow time to revise the design if the stress fails. This becomes even more critical when:

- Charge nozzle size compared to tower diameter is large. That was the case in one project where the ratio of the new charge nozzle diameter to the tower diameter became 1:4 while pre-revamp ratio was 1:10.
- Liquid fraction in the transfer line at upset condition is large compared to normal operation. This is the case when the relief-valve pressure is set close to or above atmospheric conditions.

Early-stage stress analysis evaluation allows time to determine if the charge nozzle and transfer line are too large to handle the stress forces. Re-designing the tower to handle two opposite smaller charge nozzles may prove to be the only feasible design. Obviously, early identification of such an issue will help avoid engineering re-work, schedule delays and cost escalation at a later stage of the project.

Vacuum tower, heater and transfer line relationship. A typical design consideration in vacuum heaters is meeting the minimum mass velocity and maximum choking velocity. Minimum mass velocity ensures that coking is avoided while maximum choking velocity sets the hydraulic limit of the flow. Usually, the fired heater is designed to meet both velocity specifications at normal conditions. Process engineers may not rigorously check the vacuum heater design for the turndown case, which may seriously lead to choking and/or coking problems.

At turndown conditions, pressure drop across the transfer is lower than experienced at normal conditions. Assuming constant flash-zone pressure, the vacuum heater outlet pressure will be lower at turndown, requiring lower outlet temperature but also resulting in lower vapor density and higher fluid velocity. This higher velocity may exceed the choking velocity in the furnace. This scenario might be worse when the vacuum system has no turndown adjustment mechanism to change the operating pressure, resulting in even lower pressure in the tower and at the outlet of the fired heater.

To avoid such a design mishap, detailed process conditions at turndown should be supplied to the vendor. If this issue was found to be applicable, then consider these steps:

- For initial design, the vendor should be instructed to design the vacuum tower to adequately handle the normal design rate to meet choking and mass velocities criteria.
- The vendor should also be asked to design the vacuum furnace to meet the mass velocity criteria at turndown.
- The pressure drop across the transfer line at turndown should be calculated at various flash zone pressures until the choking velocity at the outlet of the vacuum furnace is met.

As a result, at turndown, operating pressure in the vacuum tower, in this case, should be increased to meet the choking velocity criteria.

Pressure control options. Pressure control of the vacuum tower should be considered to provide flexibility and the ability to manipulate the process at turndown and high *C* -factor conditions. One or more of the following mechanisms could be considered to control the pressure for the vacuum tower:

- Design the vacuum system with multiple vacuum ejectors operating in parallel in each stage, where one or more ejectors can be isolated for turndown purposes.
- Apply spillback, steam-injection or inert-injection technique to the vacuum system to control pressure. A spillback technique, where vapor from the outlet of the first-stage ejectors is recycled through a pressure-control valve back to the suction of the same ejectors, has the advantage of not injecting additional load to the system. The spillback should be designed for self-draining away from the control valve to avoid steam condensation and freezing, and blocking the spillback line. Drainage nozzles are not helpful since the line operates at vacuum.

Updating the model. In revamps projects, pushing the tower to handle higher flows changes the pressure profile of the tower. For tray and packing towers, higher vapor/ liquid traffic results in higher pressure drop. Conversely, replacing the trays with packing may reduce the pressure drop even at higher vapor/ liquid traffic.

Attention should be given to update the simulation model and the vacuum system suction pressure specifications once the vendors send their recommendations and hydraulics data sheets. The updated simulation pressure profile, vapor/ liquid traffic and physical properties should be sent back to the vendor for further evaluation. When vacuum towers are pushed to their hydraulic limit, a small change in operating pressure may push the hydraulic capacity and *C* -factor to above or below the maximum limit.

Also, vacuum-system suction pressure specifications must be updated. Usually, the vacuum tower flash-zone pressure is the main design consideration. The suction pressure of the vacuum system is specified as the result of subtracting the tower pressure drop from the flash-zone pressure. Failure to update the suction pressure might result in too low flash-zone pressure; thus, entrainment and/or flooding due to higher vapor velocity and *C* -factor may occur.

Heat integration. As typical crude units are heat integrated, changes to tower operating temperatures and pumparound duties will have a ripple impact on the entire unit. For example, if the LVGO P/A heat exchanger (Fig. 4) is replaced with a higher surface area to provide higher P/A duty, downstream preheat-train heat exchangers would operate at reduced duty due to lower LMTD. When a full-heat integration study is not desired, these techniques (subject to plant operating conditions and equipment capacities) can be followed to minimize equipment modifications as shown in Fig. 4:

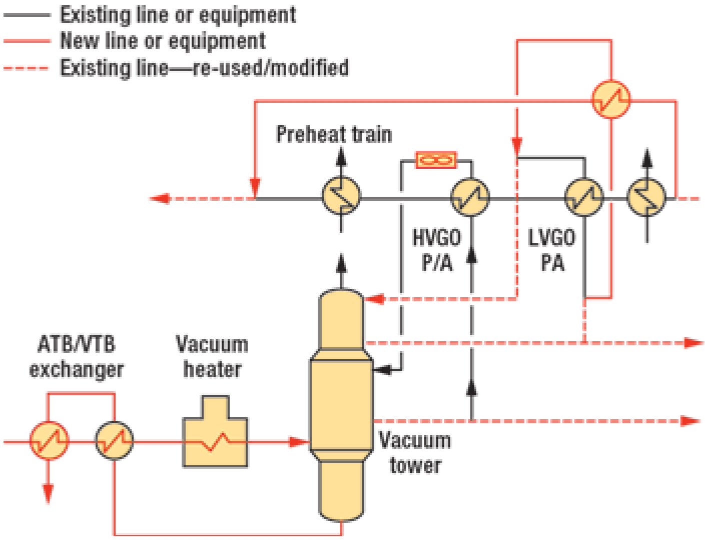

Fig. 4 Retrofitted vacuum unit with emphasis on heat integration.

- Changes to the existing P/A flow rates should be minimized to reuse the existing pumps and piping and avoid heat exchanger replacement due to hydraulic and vibration issues. More duty can be recovered by installing new air/ water coolers or integrated heat exchangers downstream of existing P/A exchanger to maintain the LMTD and duty of the existing exchangers and minimize impact on other heat integrated loops. For example, this was applied for HVGO P/A in Fig. 4.
- Higher P/A flow rates and duties could be handled by adding new heat exchangers in parallel to the existing ones rather than in series in order to split the flow and avoid hydraulic issues. This is shown in Fig. 4 for the LVGO P/A.
- To overcome heat pinch points, a second heat exchanger should be installed in series. For example, a VTB/ATB exchanger in Fig. 4 is revamped by replacing the existing exchanger bundle to handle higher throughput. A second heat exchanger is added in series to overcome temperature pinch and elevate feed temperature to the vacuum furnace. This reduces the new required duty for the vacuum furnace.

Outlook. Several considerations should be examined when revamping vacuum towers. Factors that govern vacuum tower revamps can be summarized as the operating conditions, tower hydraulic capacity, vapor distribution, product specifications, vacuum system, tower spacing, vacuum heater, transfer line, model development and heat integration. Early awareness of such issues enables the process engineer to better identify vacuum-distillation unit modifications at the front-end stage to avoid undesired cost escalations, start-up difficulties and operating issues at a later stage. **HP**

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