Designing vacuum units

When designing vacuum units for processing heavy Canadian crudes, reliability costs can be high if the feedstock's thermal instability is not fully appreciated. Process design considerations affecting VGO yield and quality are discussed

Scott W Golden and Tony Barletta
Process Consulting Services Inc

New vacuum unit capacity is currently being added at several North American refineries to process higher amounts of heavy Canadian crude. Many other refiners are evaluating revamps or new units. Ultimately, coker unit capacity will determine the maximum amount of heavy Canadian crude refiners can process. Nonetheless, maintaining a high vacuum gas oil (VGO) yield throughout the run will reduce the coker charge rate, decrease the amount of coke produced per barrel of crude, and permit maximum processing of heavy crudes.

Heavy Canadian crude oil properties influence vacuum unit reliability, VGO yield, gas oil quality and run length. Few refiners currently process high percentages of these crudes in their crude blend. Furthermore, oil sands-based crudes are less thermally stable than conventional crudes, with asphaltene precipitation and vacuum heater tube coking just two of the many challenges. Operating at a low gas oil cutpoint is one solution, but this approach reduces the VGO yield, increases the coker charge rate and raises coke production per barrel of crude.

Heavy Canadian crude oils

The implications of crude source on vacuum unit design cannot be overstated. Heavy Canadian oils consist of conventional heavy and oil sands-based crude oils. Cold Lake and Western Canadian Select are examples of conventional heavy crude. Oil sands-based crudes include Albian Heavy, Christina Lake, McKay River and others that have not yet come into production. Total conventional heavy Canadian crude production today is approximately 500Mbpd, which is expected to drop slowly until 2010 and then sharply decline. Conversely, oil sands-based production will increase from about 1000Mbpd today to about 2500Mbpd or more by 2015, depending on how many of the planned upgrader projects are actually built, when they reach full production or whether there is sufficient blendstock for the bitumen.

Applying conventional design practices to new units that will process heavy Canadian crudes will result in many unwanted surprises. Oil sands-based crude oils are generally less thermally stable than conventional crudes, some are very unstable, most have high volatile vanadium and nickel content in the VGO boiling range, many have high solids content and several have very high total acid number (TAN) in the VGO boiling range. Rapid equipment coking and asphaltene precipitation are major problems facing refiners. In some instances, heater outlet temperatures have been reduced below 700°F to obtain reasonable heater run lengths at the expense of a low gas oil cutpoint.

Crude processing flexibility will largely depend on equipment metallurgy. Some oil sands-based crude oils produce heavy vacuum gas oil (HVGO) product with TAN values of 6–8. Processing high percentages requires 317L SS in many of the circuits. Since the crude supply situation is still developing, metallurgical selection may be the difference between processing low-cost crudes and having to compete with other refiners for the low-TAN feedstocks. If most new units are built to process only low-TAN crudes to minimise investment, crude flexibility will be limited or high corrosion rates in some circuits will be the consequence of processing high-TAN crudes. Price differentials between low- and high-TAN heavy sour Canadian crude will dictate whether metallurgy upgrades will pay off.

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Crude composition variability

Conventional and oil sands heavy Canadian crudes are blends of condensate or upgrader products and very heavy crude or bitumen. Many are currently produced in limited volumes. Thus, it is prudent to assume crude composition will likely be different than the current assays when commercial production begins. The same has been true of extra-heavy Venezuelan blends; there have been significant variations in compositions. Lower API gravity crude forces a higher heater outlet temperature to achieve the same VGO product cutpoint. Even though the crude source is the same, gravity variability requires operating flexibility to achieve the same distillate cutpoint.

In addition, laboratory data show that a 10°F change in temperature in the laboratory distillation device dramatically alters the rate of thermal cracking on some of these crudes. Even though laboratory devices do not reflect true cracking tendencies in the vacuum heater, they do show directionally that there is an important stability difference between conventional heavy crude oils like Cold Lake and some of the oil sands-based crudes.

Typical vacuum unit design assumes crude quality is fixed based on a given assay. An alternate approach assumes large quality variability during the design phase and determines the operating flexibility and capital cost to maintain product yield, quality and run length. Evaluating critical operating variables and estimating the VGO yield over a range of feedstock qualities is prudent. Refiners processing heavy and extra-heavy Venezuelan and Maya crude oils have experienced significant performance differences between the design and actual operation. Many of these early heavy oil projects were designed at a benchmark 1050°F TPB cutpoint, yet several achieved less than

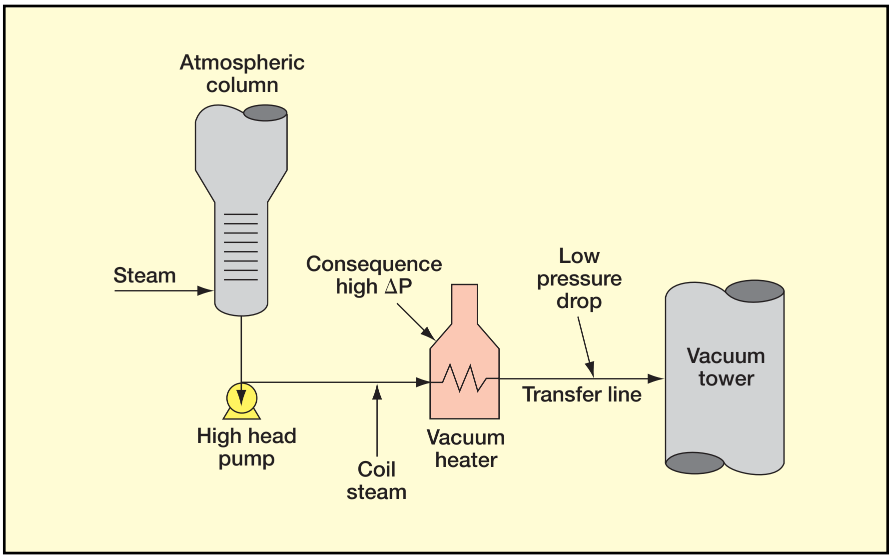

Figure 1 Vacuum unit charge system

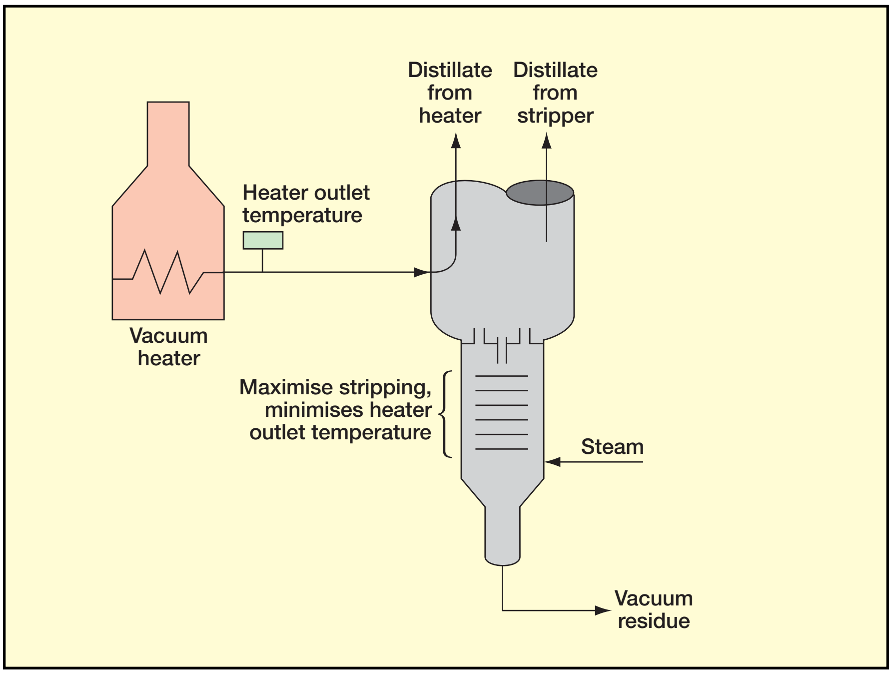

Figure 2 Minimising heater outlet temperature

1000°F when commissioned. These units produced 3 vol% less VGO and higher coker feed rates than design. In some cases, the actual crude charge rate was reduced by 8–10% to stay in balance with coker capacities.

Reducing crude oil cost is the major incentive driving these new crude and vacuum unit projects. Yet the reality is that higher capital cost designs are needed to process these crudes reliably over a four-to-five-year run length. Designing a low-cost unit will reduce project revenues, because product yields are lower and run lengths are shorter between turnarounds.

Vacuum unit reliability

Few refiners have experience of processing high volumes of either conventional or oil sands-based heavy Canadian crude oils. And these few operate at TBP cutpoints below 950°F. In some instances, major equipment design changes were needed to reliably produce high volumes of acceptable-quality VGO for four-to-five-year run lengths. In several cases, vacuum heater and column wash sections coked in less than one year. One refiner had less than one year's run on the gas oil hydrotreater due to HVGO product vanadium content of 10ppmw or more. Additional reactors were added to remove the high metals prior to the desulphurisation reactors so that reasonable run lengths were achieved in the hydrotreater.

During the design phase, it is common to perform value engineering. Typical value engineering approaches make design and equipment selection decisions based solely on a design case heat and material balance and low initial investment cost, ignoring the need for operating flexibility. While initial cost is important, building units that actually meet their design gas oil yield, quality and run length should be part of the investment decisions. Yet, many cost/performance decisions are much more complicated and involve many more unknowns than looking at only initial cost. It is easy to eliminate equipment or purchase the lowest-cost vacuum heater. However, these low-cost units will have a much lower return over the life of the unit than one that has been designed properly.

Many difficult questions must be answered. Is there a run length benefit to installing a well-designed heater vs a low-cost one when asphaltene precipitation and poor thermal stability are known problems? Is it prudent to design a double-fired heater with balanced-pass heat flux, low oil residence time and high oil mass velocity, and pay 20% more for the heater? Should the vacuum ejector system be designed for 7mmHg absolute pressure or 10mmHg, and what effects will this have on product yield and run length as well as cost? Should vacuum column wash zone internals be designed for high efficiency to reduce VGO vanadium content, knowing this increases the coking tendency? True value engineering should be performed continuously as part of the process design effort and should encompass all critical decisions influencing performance and cost, not simply initial cost.

During value engineering, someone will generally ask why a dry vacuum unit design is not being used. Dry units have much smaller vacuum ejectors, use less cooling water and steam, have a lower heater pressure drop and require a lower charge pump head, but they also produce less VGO product and more coker charge. First and foremost, vacuum units processing heavy oils must be designed with steam. Designing heaters without steam dramatically increases the rate of coke formation and decreases the run length. Those refiners who have dry units have had to reduce their heater outlet temperature to maintain a reasonable run length when processing heavy crude oils. A lower heater outlet temperature reduces the VGO yield. There are places to reduce initial investment costs; however, building a dry vacuum unit is a poor economic decision. Past experience is being ignored.

Fundamental principles drive process and equipment design. For example, because many of these crudes are thermally unstable, equipment must be designed for minimum temperature and minimum oil residence time. Figure 1 shows major components of the feed system. Lowering the oil residence time and minimising the oil temperature requires relatively high rates of coil steam injection and minimum heater tube size. This increases the system pressure drop, dictating a high charge pump head. These systems should be designed with overall performance in mind. Common practice is to send out a heater bid specification document with the maximum pressure drop based on charge pump hydraulics. Heater vendors base the heater tube size on allowable pressure drop. Vendors minimise the number of passes and make other compromises, because equipment is often purchased solely on low initial cost. This is not the vendor's fault. If the buying decision is based on price, what choice do they have? When designing vacuum units, the charge pump head is a consequence of the heater design; it should never determine the heater design.

Vacuum unit operating variables

Process and equipment design will determine the product yield, product contaminants and unit run length. Since there is little commercial experience with many of these crudes, the process engineers should be cautious when evaluating key operating variables. Since many of these crudes are less thermally stable, the heater outlet temperature should be balanced against other variables used to meet the targeted VGO yield. Flash zone pressure, coil steam rate and column stripping section performance all influence the VGO yield. Reducing the column operating pressure, decreasing the flash zone oil partial pressure by adding coil steam, or increasing the stripping section efficiency will all increase the VGO product yield. Adjusting these variables also affects capital investment and operating costs.

Meeting VGO product TBP cutpoints of 950–970°F or higher requires steam in the heater, and meeting cutpoints at or above 1000°F requires a stripping section on the column. Figure 2 shows the total vacuum distillate, which includes both the heater and stripping section contributions. Increasing the yield from the stripping section decreases the heater outlet temperature needed to meet a targeted VGO product yield. Determining the most cost-effective combination of column operating pressure, heater outlet temperature, coil and stripping steam flow rates is critical for heavy crude processing, especially at high gas oil cutpoints.

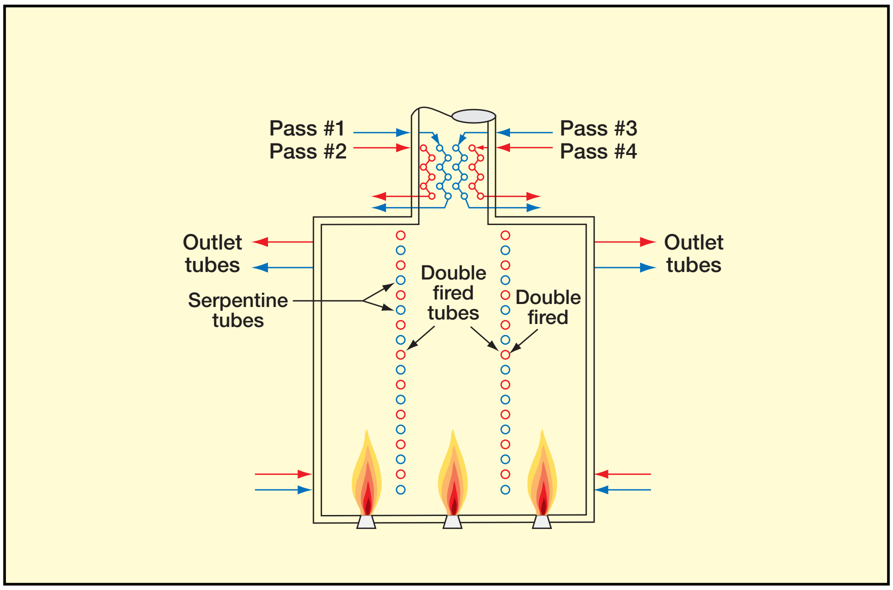

***Figure 3** Double-fired serpentine tube layout*

Vacuum heater

Fired heaters processing unstable oils or those operating at a very high temperature must be designed to avoid rapid coke formation rates. Controlling the oil film temperature and residence time is essential to minimise coking. Nevertheless, most vacuum unit fired heaters are designed by the vendors according to the process data given to them on an API 560 data sheet. As long as the vendors comply with the API guidelines, such as minimum burner spacing from the tubes, their bids are considered technically acceptable. This approach ensures a substandard heater is installed when the primary selection criterion is low initial costs. Vacuum heater designs should be specified in detail, including tube passes, tube size, tube configuration, burner layout, coil steam injection location and all other factors influencing the oil film temperature and oil residence time.

Heater outlet temperature is only one of the variables affecting coke formation, and it is a relatively unimportant variable. However, many designers assume a low heater outlet temperature will ensure a heater will not coke. Bulk oil temperature certainly contributes to heater coking, but oil cracking occurs in the oil film flowing on the inside of the tube. A poorly designed vacuum heater will dictate a lower outlet temperature and produce less VGO product yield, because the oil film temperature and oil residence time are both high. Properly designed heaters allow much higher heater outlet temperatures, producing more VGO product for the same heater run length. Critical oil film and oil residence time variables are controlled through heater design and coil steam injection.

> "When designing vacuum units, the charge pump head is a consequence of the heater design; it should never determine the heater design"

Large single-cell vacuum heaters have four to six tube passes. A well-designed heater minimises heater flux variation, although heat flux always varies from the combustion zone, where the fuel/air mixture is burned, to the flue gas outlet from the radiant section. It is lowest at the floor of the heater, highest where the greatest amount of combustion occurs, and decreases in the top of the radiant section. Each heater pass must be designed so the average heat flux is the same for each pass. Low-cost heaters are designed such that heat absorbed per pass varies significantly. The result is a higher heat flux and higher oil film temperatures in some of the passes.

Several factors including the number of burners, burner layout, burner flame length, burner-to-tube spacing, firebox height-to-width (L/D) and non-ideal flue gas flow patterns influence heat flux variability from the floor of the heater to the outlet. Since heat flux always varies, the amount of radiant section surface area in the low- and high-flux zones must be equal. One approach is to use multiple external jump-overs so the surface area in each pass is the same in the low- and high-flux zones. However, the designer must be able to predict the location of high- and low-heat flux zones. Since many factors, including burner operation (as to opposed to design), influence the location of the

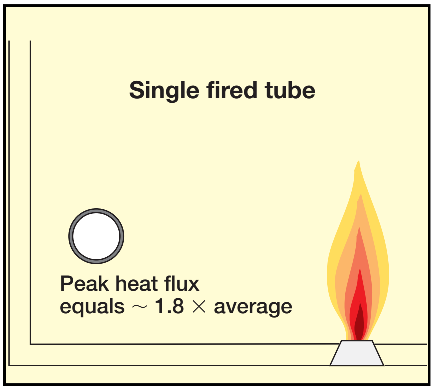

Figure 4 *Single-fired tube — high peak heat flux*

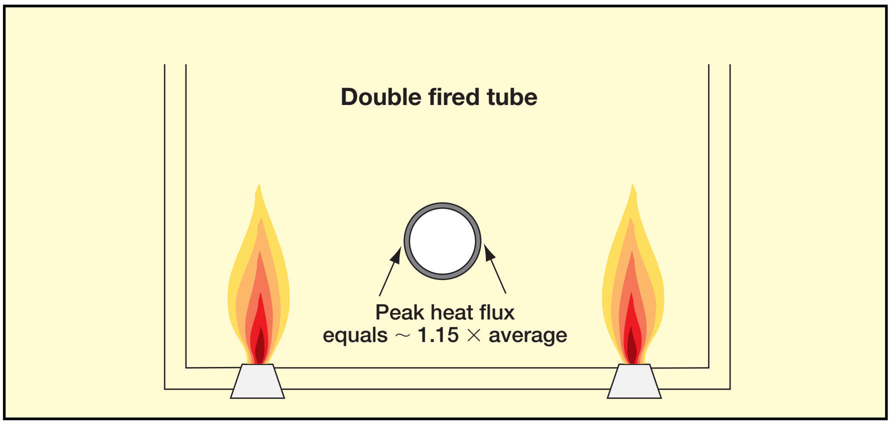

Figure 5 *Double-fired tube — much lower peak heat flux*

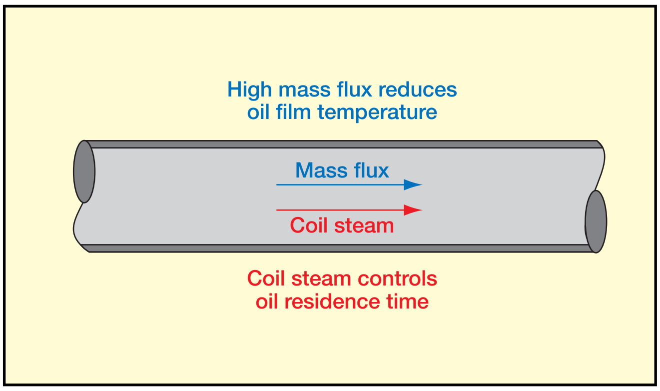

Figure 6 *Oil mass flux and coil steam function*

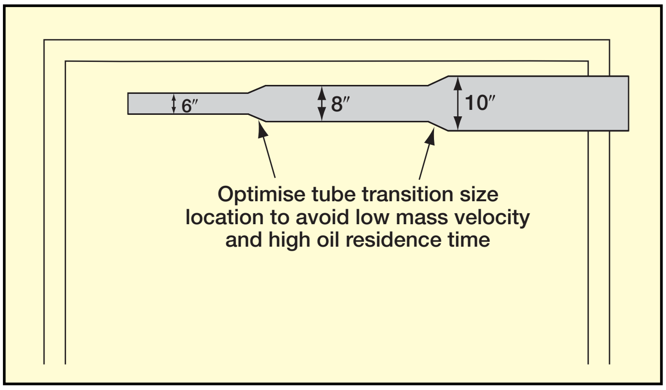

Figure 7 *Heater tube size transition location*

high- and low-flux zones, using external jump-overs does not ensure each pass absorbs an equal amount of heat. A better solution is to use a serpentine pass layout that guarantees each pass gets the same amount of heat in spite of heat flux variation (Figure 3).

Coke forms inside the radiant section tubes, because the oil film flowing along the inside of the tube exceeds the temperature and residence time needed to initiate thermal cracking. Oil film temperature depends on heat flux and oil mass velocity. Increasing the heat flux raises the oil film temperature at a fixed mass flux, while a higher mass flux lowers the film temperature at a given heat flux. Oil residence time depends on oil mass velocity, the quantity of coil steam and the radiant section tube surface area. While increasing the radiant section surface area decreases the heat flux, it also raises the oil residence time.

Bulk oil temperature plus a temperature rise across the oil film sets the film temperature. Cracking occurs where the oil film reaches its highest (peak) temperature. Peak oil film temperature depends on the peak heat flux and oil mass flux. Designs that reduce the localised peak heat flux lower the oil film temperature, allowing higher heater outlet temperatures without excessive cracking and high rates of coke formation.

t_f = Temperature drop across the oil film
= $Q_{local}\, D_o/D_i\, h_i$
= ºF (1)

Equation 1 shows how temperature drop across the oil film is calculated. The D_o and D_i are the outside and inside tube diameters respectively. Combustion zone flame radiation, flue gas temperature and single or double firing determine the amount of heat transferred locally (Q_{local}). For a given localised heat flux (Q_{local}), the temperature drop through the oil film is controlled by process fluid inside the film coefficient (h_i). Reducing the tube size increases the oil mass flux (Equation 2) and heat-transfer coefficient (Equation 3), decreasing the oil film temperature and thereby reducing the rate of coke formation.

G (mass flux) = Mass rate of oil/inside cross-sectional area of heater tube
= lb/sec-ft^2 (2)

Inside tube heat (h_i) = $(0.023)\, k/D\, (DG/e)^{0.8}\, (c_p e/k)^{0.33}\, (e/e_w)^{0.14}$
Transfer coefficient = Btu/hr-ft^2-ºF (3)

Most vacuum heaters are single fired. One side-to-tube faces the burners and the other sees only the refractory. Since the fire is on one side, the heat flux around the circumference of the tube varies greatly. The portion of the tube facing the burners has a high heat flux, while the side facing the refractory is much lower. For a single-fired tube (Figure 4) on two-to-one spacing, the peak flux is approximately 1.8 times the average for the tube. A few vacuum heaters and most modern coker heaters use double-fired tubes (Figure 5) that greatly reduce the peak flux to about 1.15–1.2 times the tube average.

Vacuum units processing low-stability crudes should use a double-fired design to reduce the peak heat flux and the peak oil film temperature. For example, a single-fired heater tube with an average heat flux of 10 000btu/hr-ft^2-°F will have a peak heat flux of 18 000btu/hr-ft^2-°F, whereas the double-fired design having the same average heat flux will have a peak heat flux of only 12 000btu/hr-ft^2-°F. Hence, peak film temperatures are significantly reduced.

Minimising oil residence time in the radiant section reduces the rate of coke formation. Oil residence time depends on the oil mass flux and coil steam rate (Figure 6). Increasing the oil mass flux and injecting the coil steam reduces the oil residence time, but it also dramatically increases the heater pressure drop, requiring a much higher pump head.

Coking in the heater outlet is a common problem. Outlet tubes have several sizes to control the pressure drop, as the oil vapourises to minimise the bulk oil temperature. In addition, two-phase mixed velocity must be kept below critical to avoid a higher operating pressure, further raising the bulk oil temperature. But a larger tube size decreases the oil mass flux, causing a higher temperature drop across the oil film. Oil vapourisation in the larger tubes increases the fluid velocity as long as the tube transition location is correct. The increased fluid velocity dramatically reduces the oil residence time, thus avoiding rapid coke formation. However, if the tube size is increased before oil vapourisation begins, the mass flux decreases, oil velocity decreases, oil residence time increases and oil film temperature increases, causing rapid coke formation. Tube size transition location must be selected so that the coking in the larger tube sizes is not a problem (Figure 7).

Column operating pressure

Column flash zone pressure, column diameter and ejector size should be optimised to meet the vacuum gas yield target while minimising the heater outlet temperature. Operating pressure, VGO yield and total steam rate set the vacuum column diameter. Since vessel diameter is a large cost issue, optimising the operating pressure is essential. Ultimately, column top pressure is selected so that the design flash zone pressure allows the unit to meets its design VGO yield at an acceptable heater outlet temperature to avoid rapid coking. The coil and stripping steam rate and design column top pressure determine the ejector system size. These variables must be carefully selected to minimise overall investment.

Column flash zone pressure depends on the design ejector inlet pressure and the pressure drop through the column internals (Figure 8). Internals should be designed for a minimum pressure drop. Since stripping section performance has a large influence on the heater outlet temperature, its efficiency should be optimised so that the stripping steam rate is minimum. Furthermore, the total coil steam and stripping steam rate should be optimised so that the booster ejector size is minimised (Figure 9).

Optimising the column operating pressure has major reliability, product yield, product quality and cost implications. Ideally, column diameter should be minimum. However, if it is too small, the heavy vacuum gas product will be of poor quality due to residue entrainment. Since volatile metals are already high in these crudes, any entrainment results in poor-quality VGO. If the design operating pressure is lower than necessary, the ejector system and column diameter are larger than necessary, raising capital costs. Conversely, a high operating pressure can increase the heater outlet temperature above the thermal cracking limit of these crude oils.

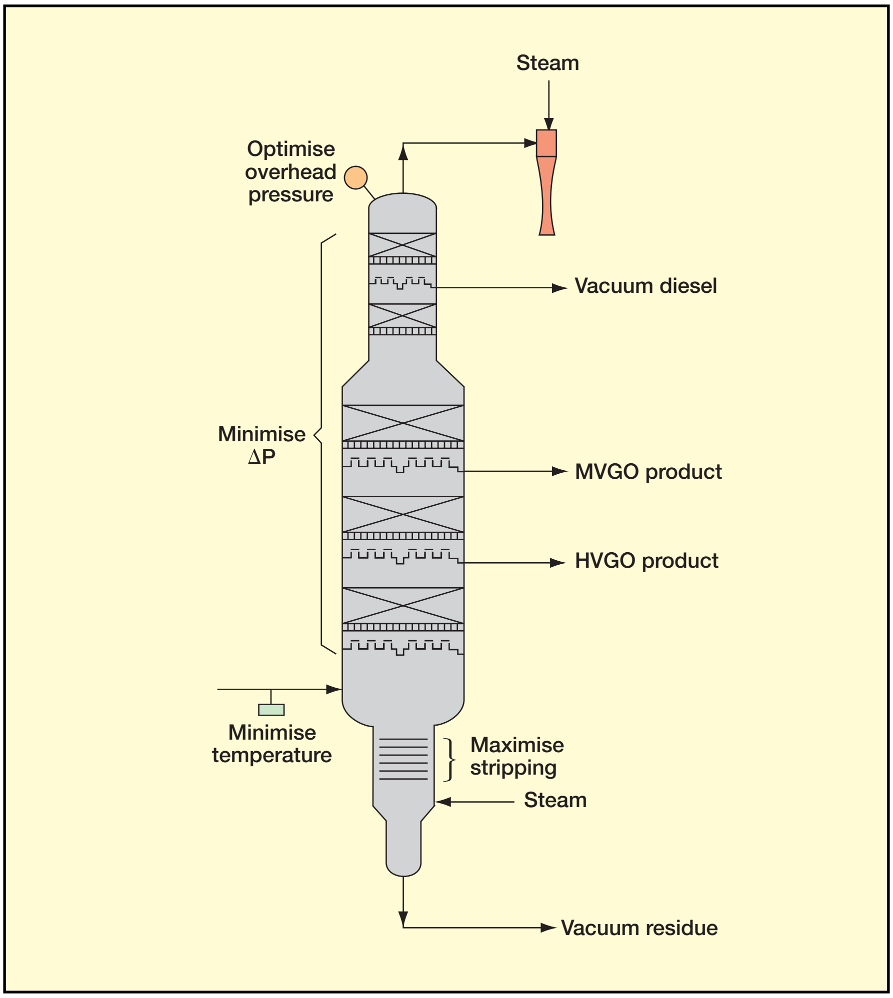

Figure 8 *Optimise column operating pressure*

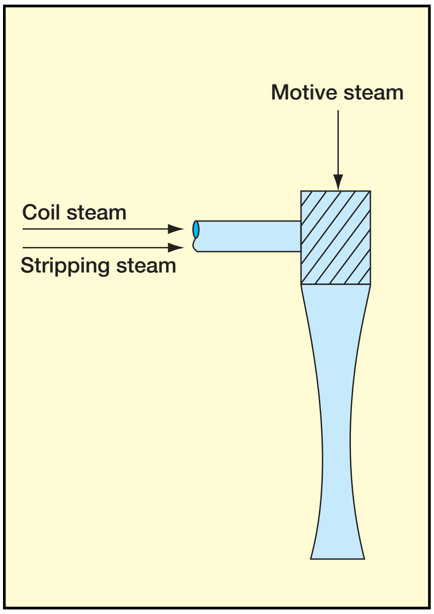

Figure 9 *Booster ejector steam load*

Conclusions

Lessons learned processing heavy Venezuelan crudes should be applied to these new projects that will process heavy sour Canadian crude oils. These units should not be designed with conventional practices used for light crudes. Heavy oil properties are very different, and design requirements will raise initial costs. These higher initial costs will pay out over the life of the project through increased VGO product yield, lower maintenance cost, reduced vanadium content gas oil and longer run length between decokings.

Scott W Golden *is a chemical engineer with Process Consulting Services Inc in Houston, Texas, USA. He holds a BS degree in chemical engineering from the University of Maine.*
Email: sgolden@revamps.com
Tony Barletta *is a chemical engineer with Process Consulting Services Inc in Houston, Texas, USA. He holds a BS degree in chemical engineering from Lehigh University. Email: tbarletta@revamps.com*