Understand vacuum-system fundamentals

Properly operating ejectors and condensers is important
in maximizing vacuum tower gas-oil yield

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Crude vacuum unit heavy vacuum gas-oil (HVGO) yield is significantly impacted by ejector-system performance, especially at conditions below 20 mmHg absolute pressure. A deepcut vacuum unit, to reliably meet the yields, calls for proper design of all the major pieces of equipment. Understanding vacuum ejector system impacts, plus minimizing their negative effects equals maximum gas yield. Ejector-system performance may be adversely affected by poor upstream process operations.

The impacts of optimum ejector performance are more pronounced at low flash-zone pressures. Gas-oil yield improvements for small incremental pressure reductions are higher at 8 mmHg than at 16 mmHg. Commercial operation of a column with a 4.0 mmHg top pressure and 10 mmHg flash-zone pressure is possible. Designing a deepcut vacuum unit calls for a balance between practical limits of furnace design, column diameter, utility consumption and ejector-system size. Commercial performance of a deepcut vacuum unit operating at a HVGO true boiling point (TBP) cutpoint of 1,150°F highlights the impact of off-design ejector performance on gas-oil yield. Understanding the vacuum ejector-system fundamentals is critical to maintaining gas-oil yields.

Ejector-system performance at deepcut vacuum column pressures may be independently or concurrently affected by:

- Atmospheric column overflash, stripper performance or cutpoint

- Vacuum column top temperature and heat balance

- Light vacuum gas-oil (LVGO) pumparound entrainment to the ejector system

- Cooling-water temperature

- Motive steam pressure

- Non-condensible loading, either air leakage or cracked light-end hydrocarbons

- Condensible hydrocarbons

- Intercondenser or aftercondenser fouling

- Ejector internal erosion or product build-up

- System vent back pressure.

Minimizing ejector-system gas loading lowers column pressure, thereby increasing gas-oil yield. By optimizing process performance when processing West Texas Intermediate (WTI) crude, the
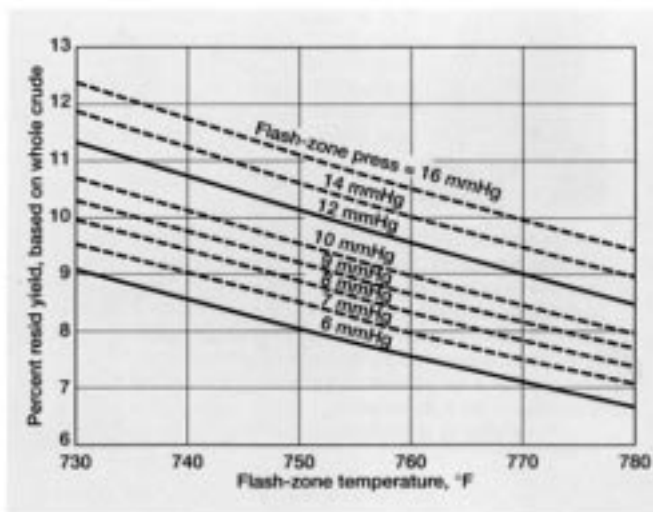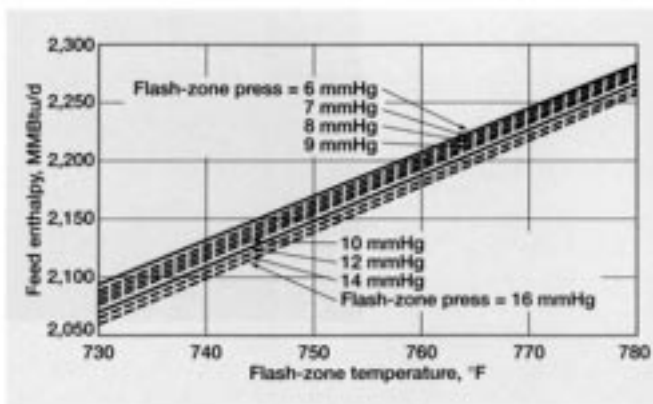

Fig. 1. Gas-oil yield.

Fig. 2. Feed enthalpy vs. temperature.

gas-oil yield can be increased by 0.75 vol%. This represents 1,150 bpd of incremental gas-oil recovery for a 150,000-bpd refinery. Assuming an average $5/bbl gas-oil differential over vacuum residue, incremental annual revenue is $2 million. Experience with deepcut vacuum unit operation on WTI crude has shown that vacuum column pressure is strongly impacted by atmospheric column operation and LVGO pumparound operation.

Fig. 3. Ejector components and pressure profile.

GAS-OIL YIELDS

The gas-oil yield on a crude vacuum column is controlled by feed enthalpy. If more heat can be added to the reduced crude at a given column pressure, more oil is vaporized. A good furnace design is required to reliably meet the coil outlet temperature requirements of a deepcut operation without excessive cracked-gas production.

Fig. 1 shows the impact on gas-oil yield, assuming a given quality of WTI reduced crude. The curves are in terms of vacuum residue yield as a percent of whole crude. Fig. 2 represents feed enthalpy as a function of temperature and pressure. Figs. 1 and 2 are based on the same atmospheric residue composition assuming a crude unit charge of 40,000 bpd. The effect of column temperature and pressure on gas-oil yield is highlighted. Gas-oil yield improvements for small incremental pressure reductions are higher at low column pressures than at higher pressures.

For example, a 2 mmHg pressure reduction is made for columns operating at 16 mmHg and 8 mmHg. Both have a constant flash-zone temperature of 760°F. Lowering pressure from 16 to 14 mmHg and from 8 to 6 mmHg will increase gas-oil yield by 0.46% and 0.77%, respectively. This trend is more dramatic for larger spreads in operating pressures. The column top pressure varied between 4 and 16 mmHg and was caused by the process and utility systems.

It is important to achieve lower pressures while meeting the practical limits of furnace design and minimizing cracked-gas formation. Example: a vacuum unit is to minimize residue yield to 9% based on whole crude. From Figs. 1 and 2 a column operating at 6 mmHg and 730°F flashzone pressure and temperature will have the same gas-oil recovery as a column at 14 mmHg and 780° F. These two cases have a feed enthalpy differential of 171.5 MMBtu/d with the higher pressure requiring a higher feed enthalpy.

EJECTOR-SYSTEM FUNDAMENTALS

Gas load. The ejector-system loading consists of:

- Non-condensibles like cracked gas from the furnace and air leakage

- Condensible hydrocarbons carried with non-condensibles

- Entrainment

- Furnace coil steam

- Tower stripping steam.

Non-condensibles and a small amount of condensible gases are generated in the furnace. Cracking is most severe in dry vacuum-tower operations with furnace-outlet temperatures above 750°F. A proper furnace design will minimize cracked hydrocarbon gases. Deep-cut operations with insufficient quench to the tower boot can also cause cracked-gas formation. The quench distribution quality to the boot should be included in the vacuum tower design. Ejector load is also affected by poor crude stripping in the atmospheric crude tower. Cause: damaged or an insufficient number of stripping trays, improperly designed trays or insufficient stripping steam.

Theory. The operating principle of an ejector is to convert pressure energy of the motive steam into velocity. This occurs by adiabatic expansion from motive steam pressure to suction-load operating pressure. This adiabatic expansion occurs across a converging and diverging nozzle (Fig. 3). This results in supersonic velocity off the motive nozzle, typically in the range of mach 3 to 4. In actuality, motive steam expands to a pressure lower than the suction load pressure. This creates a low-pressure zone for pulling the suction load into the ejector. High-velocity motive steam entrains and mixes with the suction gas load. The resulting mixture's velocity is still supersonic.

Next, the mixture enters a venturi where the high velocity reconverts to pressure. In the converging region, velocity is converted to pressure as cross-sectional flow area is reduced. At the throat section, a normal shock wave is established. Here, a dramatic boost in pressure and loss of velocity across the shock wave occurs. Flow across the shock wave goes from supersonic ahead of the shock wave, to sonic at the shock wave and subsonic after the shock wave. In the diverging section, velocity is further reduced and converted into pressure. Fig. 3 shows ejector components and a pressure profile.

Motive pressure, temperature and quality are critical variables for proper ejector operating performance. The amount of motive steam used is a function of required ejector performance. The nozzle throat is an orifice and its diameter is designed to pass the specified quantity of motive steam, required to effect sufficient compression across the ejector. Calculation of a required motive nozzle throat diameter is based on the necessary amount of motive steam, its pressure and specific volume. The following equation found in the Heat Exchange Institute Standard for Steam Jet Ejectors is commonly used to determine throat diameter:
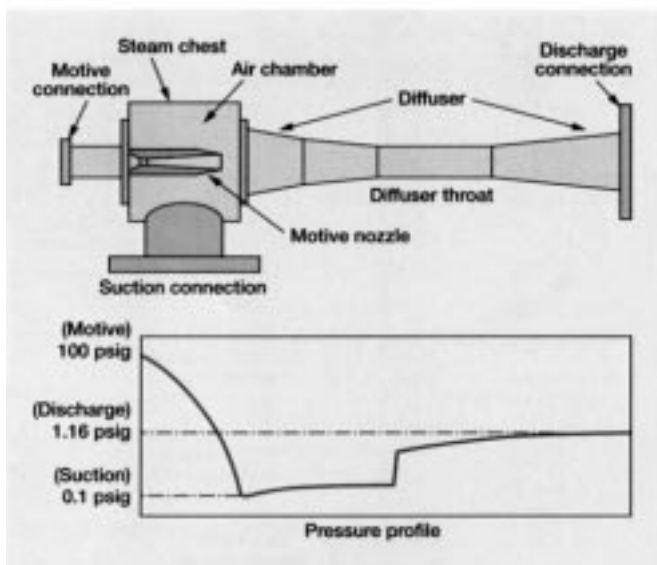
lb/hr motive steam = 892.4 $C_d D_n^2 (Psia/Vg)^{0.5}$ where
  Cd = Nozzle discharge coefficient
  D = Nozzle throat diameter, in.
  $Psia$ = Motive steam pressure at ejector, lb_f/in^2
  V_g = Motive steam specific volume, $ft^3/1b$.

Motive steam quality is important because moisture droplets affect the amount of steam passing through the nozzle. High-velocity liquid droplets also prematurely erode ejector internals, reducing performance.

Operating a vacuum unit requires an ejector system to perform over a wide range of conditions. Loads vary from light to above design. The ejector system must be stable over all anticipated operating conditions. Determinating design air leakage and light-end hydrocarbon loading is essential to stable operation of the vacuum system. Furthermore, an accurate understanding of ejector-system back pressure for all operating modes is necessary for stable operation. An ejector does not create its discharge pressure, it is simply supplied with enough motive steam to entrain and compress its suction load to a required discharge pressure. If the ejector back pressure is higher than the discharge pressure it can achieve, then the ejector "breaks" operation and the entire ejector system may be unstable.

Compression ratio. The ratio of discharge pressure to suction pressure is the ejector compression ratio. These normally vary from 3 to 15. An ejector's individual compression ratio is a function of cooling-water temperature, steam use and condensation profile of hydrocarbons handled. The first-stage ejector, tied directly to column discharge, will have a compression ratio set primarily by intercondenser cooling-water temperature.

Intercondenser capital cost, steam costs and cooling-water requirements should be balanced against first-stage ejector design discharge pressure. This pressure must be high enough for condensation to occur in the intercondenser. With 85°F cooling water, an initial steam condensing temperature of 105°F is reasonable. This corresponds to a first-stage intercondenser operating pressure of approximately 60 mmHg. But, other condenser operating pressures are possible. If a lower operating pressure is considered, this lowers the available log-mean temperature difference (LMTD) and, thus, increases intercondenser cost. But, less motive steam is required. If a higher operating pressure is used, more motive steam is needed to permit compression to that higher pressure. Capital and operating costs are balanced to optimize overall system cost.

A deepcut column with an operating pressure of 4 mmHg will normally have a three-stage ejector system. Some columns have design top pressures below 4 mmHg and as low as 1.5 mmHg. These columns may have four-stage ejector systems. A four-stage system will have two ejectors in series compressing column overhead load to the first intercondenser operating pressure.
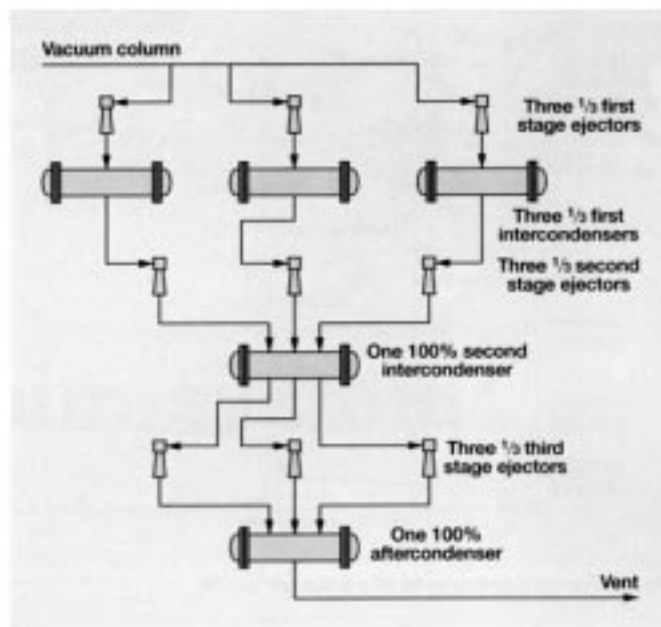

Fig. 4. Three-stage vacuum system.

CONDENSERS

Intercondensers are positioned between ejectors. The aftercondenser is located after the last ejector. There is an interdependency between the ejectors and condensers. Both must perform satisfactorily for proper system operation. Condenser performance is affected by:

• Cooling-water temperature, flowrate and temperature rise

• Non-condensible loading

• Condensible loading

• Fouling

• Height of barometric leg.

The first intercondenser is the largest and primary condenser in the vacuum system. But, the second intercondenser and aftercondenser are also key to proper overall system operation. In the past, direct-contact barometric condensers were commonly used. However, shell-and-tube condensers are primarily used now. They condense motive steam and condensible hydrocarbons, and cool non-condensible gases normally on the shell side. Cooling water is typically on the tubeside.

Configurations. The ejector system may be configured a number of different ways to handle various crudes and differing refinery operations. It is possible to use a single vacuum train consisting of one set of ejectors and condensers. This allows minimal initial investment but limits flexibility in controlling utilities or managing different crudes and varying unit operations. Often, parallel ejectors are installed for each stage. Each parallel ejector will handle a percentage of total loading, i.e., twin-element ejectors each designed for 50% of design load, triple-element ejectors each designed for 40% of design load for 120% capacity, or twin-element ⅓ – ⅔ ejector trains.

Note:
1. Tailpipe height should be 34 ft for water and 45 ft for hydrocarbon as a minimum. Density correction factors should be considered.
2. If the hotwell operates above atmospheric pressure, adjust the tailpipe height. You can calculate the height using the following relationship:

$$\text{Height, ft} = \frac{(\text{Hotwell pressure}) \times (2.31)}{\text{Specific gravity}}$$
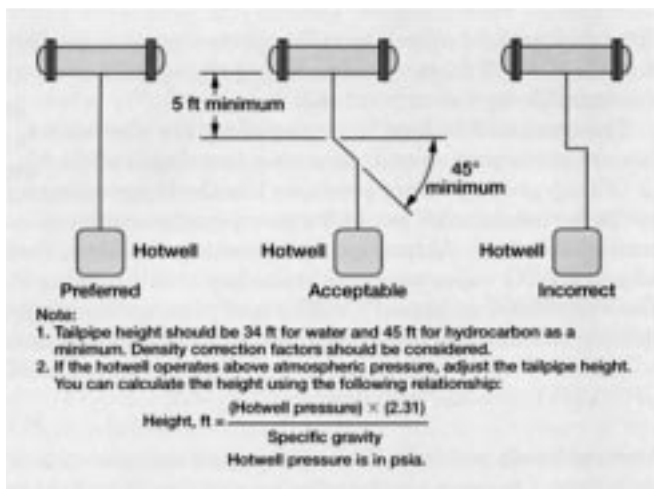
Hotwell pressure is in psia.

Fig. 5. Intercondenser tailpipe arrangement.

Parallel ejector trains allow one train to be shut down for maintenance while the column operates at a reduced load. At light loads, a train may be shut down to reduce operating costs. Fig. 4 shows a typical deepcut vacuum system with triple-element ejectors and first intercondensers. The second intercondenser and aftercondenser are both single elements.

VACUUM-SYSTEM TROUBLESHOOTING

Commissioning. Before startup, the ejector system should be isolated from the column and load tested to see if air leakage occurs. Each ejector will have a "no-load" suction pressure, supplied by the ejector manufacturer. No-load suction pressures attained in the field should be compared to manufacturer data. If the design no-load suction pressure cannot be met, the cause should be identified prior to startup.

Operation. Column overhead pressure rising above the design maximum pressure may be the result of increased unit throughput, furnace problems or atmospheric column internal damage. These process conditions result in increased column overhead gas rate and are not necessarily a problem for the ejector system. A first-stage ejector will have an operating curve, usually provided by the manufacturer, that indicates column top operating pressure maintained by the ejector as a function of mass loading. As overhead mass flowrate increases above design, so will column overhead pressure. The converse is also true to a point.

The ejector system will track this performance curve provided design air leakage or non-condensible hydrocarbon loading is not exceeded. If this happens, the first ejector will follow its performance curve. However, the secondary ejectors are affected. Due to an increase in non-condensible loading, a subsequent increase in saturated condensible loading from the first intercondenser results. As non-condensible loading increases, the amount of steam and hydrocarbon condensed decreases. The increased gas loading exiting the first condenser cannot be handled by the second-stage ejector at the intercondenser design operating pressure. Furthermore, the first-stage ejector does not have enough energy, nor are its internals designed to compress the load to a high

enough pressure to allow the second-stage ejector to handle the increased intercondenser gas discharge. As a consequence the first-stage ejector breaks operation and tower pressure rapidly increases and may become unstable. A similar situation may also occur between the second- and third-stage ejectors.

Unstable column operation can also result from poor steam conditions. If the steam pressure at any ejector falls below design, then less steam will pass through the motive nozzle. This results in insufficient steam for compression across the ejector. Excessive superheat will have a similar effect since less steam passes through the nozzle. Accurate assessment of steam conditions is critical. If steam pressure is below design or if excess superheat exists, the motive nozzle must be rebored to a larger diameter. After boring, it is necessary to smooth the internals and remove rough edges so that flow coefficients are not impacted.

High steam pressures are normally acceptable as long as they are within 110% to 120% of design. If steam pressure is too high, then too much steam passes through the nozzle, choking the diffuser throat and reducing the load handled. If this occurs, new nozzles must be installed or steam pressure controlled closer to design.

Wet steam causes erosion of ejector internals. This reduces ejector capacity and may cause erratic operation. Moisture droplets accelerated to supersonic velocities are very erosive on the motive nozzle, inlet diffuser and exhaust elbows or condenser tubes. Steam lines must be insulated up to the ejector motive nozzle. A steam separator and trap must be installed before each ejector. Steam traps require periodic inspection to ensure they properly dump condensate. If the motive nozzle or diffuser show excessive wear (cross-sectional area increase in excess of 7% of design) then they must be replaced.

If a condenser becomes fouled, it will not properly condense and cool gases to the design outlet temperature. This increases gas loading to the following ejector, which is unable to handle the condenser's design operating pressure. This leads to "breaking" of the preceding ejector. Condensers should be periodically cleaned and maintained in a usable condition.

Insufficient cooling water will similarly affect ejector performance. This problem reduces overall heat-transfer rate and increases the water temperature rise. A higher temperature rise lowers LMTD. This effect has the largest impact on the first intercondenser. If the overall heat-transfer rate and LMTD fall below design, condenser performance is compromised. The net result is that proper condensation and gas cooling does not occur and the ejector overloads. Therefore, the ejector system may operate in a "broken" condition. Cooling-water supply should be maintained at high enough flow to meet the design LMTD at design heat loads.

Good condenser performance is needed the most during the summer. At this time, cooling water is the warmest and refinery cooling demands are highest. Proper determination of cooling water availability, temperature, operating pressure and pressure drop is key to proper ejector system performance. Periodic field surveys should be performed.
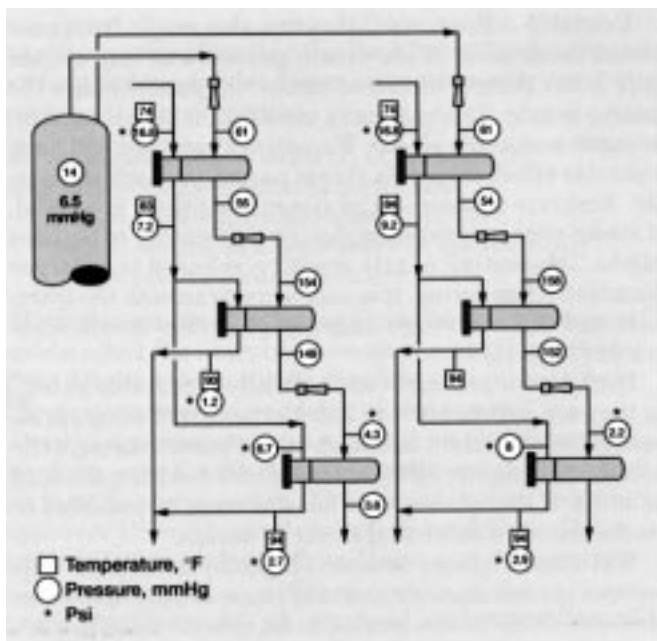
Fig. 6. Ejector system survey, high pressure.

Improper barometric leg (condensate drain) layout has a negative effect on condenser performance. Condensate drains by gravity, so the barometric leg must be high enough to ensure that condensate does not enter and flood the condenser. Flooding lower tubes makes them ineffective for heat transfer. The barometric legs should be at least 34 ft above the condensate receiver for 100% water condensate. With mixed water and hydrocarbon condensates, a barometric leg of at least 42 ft is required. If condenser flooding occurs, check the drain legs for blockage. Also, horizontal drain leg runs are not recommended because they are susceptible to gas pockets. Fig. 5 has recommended barometric leg layouts. If a condensate receiver operates above atmospheric pressure then the barometric leg height must be increased.

If the system back pressure, or back pressure on any ejector, increases above its design discharge pressure, then that ejector may operate in an unstable or broken condition. This occurs because the ejectors' internals are not designed to compress to a higher discharge pressure. Also, there is insufficient steam to do the necessary work.

TABLE 1. SLOP OIL ASTM D86 DISTILLATION

Vol%	Temperature, °F
0	133
5	198
10	210
20	223
30	235
40	246
50	262
60	278
70	309
80	385
90	509
100	643

PROCESS OPERATIONS

Once the ejector system is designed and the utility-system performance is established, process operations will dictate ejector-system performance. Air leakage and non-condensible production from the vacuum unit fired heater is set for a given system volume and furnace performance. Furnace non-condensible production can be controlled by coil steam injection. Coil steam will load the ejector system. Hence, the optimum coil steam versus cracked gas production impacts vacuum once the system is built. Here, we will assume that non-condensible and coil steam load on the ejector system are constant. Lieberman[2] covered the importance of furnace design and operations on ejector-system performance. We will focus on controlling the ejector-system condensible hydrocarbon load.

The condensible load is impacted by the atmospheric column performance and vacuum column operation. The LVGO top product vapor pressure has the biggest impact on ejector condensible load for a given ejector-system noncondensible load. Assessing the operating variables that impact LVGO vapor pressure is the key to minimizing it. The variables that impact LVGO vapor pressure are atmospheric column overflash, stripper performance and cut-point; and vacuum column top temperature and LVGO/HVGO material balance.

Atmospheric column. This design and operation has a significant impact on the ejector system. For lighter material being fed to the vacuum column, LVGO vapor pressure will be higher at a given temperature. The atmospheric column stripping section and wash section affect the vacuum column condensible load. Minimizing atmospheric column overflash is important. The stripping section performance is affected by steam rate (lb steam/bbl atm. residue). Maximizing stripping-section performance is the largest, and least costly operating tool to maximize vacuum column ejector-system performance. Atmospheric column cutpoint is also important. The order of importance is:

- Stripping section
- Overflash
- Atmospheric residue cutpoint.

Vacuum column. The top temperature should always be minimized and the quantity of LVGO maximized. LVGO pumparound rate and return temperature must be optimized within the constraints of entrainment to the overhead system and LVGO pumparound circuit exchanger LMTD. Minimizing the pumparound return temperature will lower condensible load for a given exchanger surface area and utility. There are some trade-offs because the return temperature and LVGO yield influence condensible load.

The pumparound condenses hydrocarbons before the ejector system. The quantity of condensible hydrocarbons to the ejector system is a function of the quantity of noncondensibles and the lightest-condensible material's vapor pressure. Minimizing top temperature minimizes first-stage ejector vapor load.
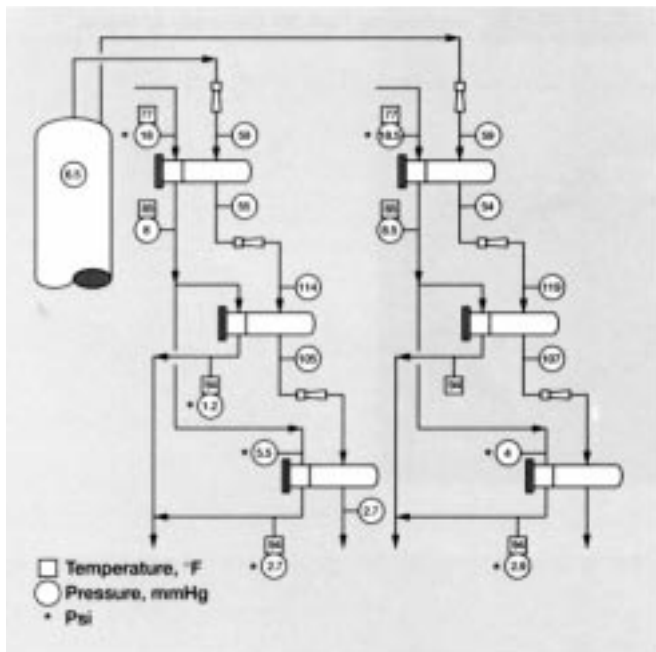
Fig. 7 Ejector system survey, low pressure.

The column packing internals and liquid distributor may be viewed as a direct-contact heat exchanger. Poor heat-transfer performance, due to vapor-distribution problems or poor liquid distribution, will increase the ejector condensible load. The top pumparound system design is critical for optimum ejector performance. In the past, many of these distributors were spray headers. A modern, high quality gravity distributor will reduce entrainment and reduce ejector condensible loading.

Pumparound spray header distributors are susceptible to plugging, especially if no strainers are provided. Plugging results in liquid maldistribution. Even with conservative packed-bed depths, inherent packing distribution is often not sufficient to recover from maldistribution. Trayed vacuum towers are often revamped with packed designs that reuse existing draw pans. But these draw pans are usually designed with vapor risers that are too large and too few in number for packed applications. The pumparound return temperature and heat-transfer efficiency of the pumparound tower internals set the hydrocarbon vapor equilibrium. Either poor heat transfer or high pumparound return temperatures will increase ejector load.

An improperly-designed spray header can produce sufficient entrainment to overload the vacuum system or reduce intercondenser heat-transfer capability by waxing the condenser tubes. The spray-header system design requires even irrigation to the packing's top. Nozzles to minimize mist formation are critical. The spray header design must provide a sufficient operating range while not exceeding high nozzle pressure drops that produce high quantities of mist-size droplets. Our experience has shown that a nozzle pressure drop of 15 psi is typically a good maximum. This varies by nozzle selection.

CASE STUDY: DEEPCUT OPERATION

A new vacuum unit was designed to operate at a HVGO TBP cutpoint up to 1,150°F. One of the design flash-zone operations was a temperature of 770°F at 12 mm Hg absolute pressure. The vacuum ejectors were designed for an overhead pressure of 4 mmHg. The vacuum overhead pressure varied after unit commissioning. The minimum top pressure was typically 6.5 mmHg. A 2.5 mmHg reduction to achieve the design value would result in an additional 0.8% gas-oil yield based on whole crude (Fig. 1). Optimizing an operating unit to obtain minimum overhead pressure is challenging. Some of the modifications implemented had some interesting results.

Ejector system survey. This showed that the column design top pressure could not be obtained. And a marked deterioration occurred at higher crude charge rates. A survey of the overhead ejector system was done at a crude charge rate of 35,000 bpsd (Fig. 6) and again at a charge rate of 52,000 bpsd (Fig. 7). The column overhead pressure was 6.5 mmHg and 14 mmHg absolute, respectively. The pressure surveys were conducted with an absolute pressure manometer to ensure accurate pressure readings. Non-absolute pressure manometers are not recommended since they are affected by changes in barometric pressure and elevation.

Process impacts. There are two approaches to troubleshooting any process problem. Try something and see what happens or study the problem. The first approach was to make a change and see what happens. One theory to account for the reduced performance was that wax was forming on the condenser surface from entrained LVGO. But wax was not observed during previous intercondenser inspections. An improperly-designed spray header can produce sufficient entrainment to overload the vacuum system or reduce the heat-transfer capability of the intercondenser by waxing the condenser tubes. Then, we reduced the pumparound flowrate from 30,000 bpd to 19,000 bpd. We observed that:

- Top column pressure lowered by 4 mmHg to 9 mmHg

- Pumparound return temperature lowered from 125°F to 115°F

- Lower top column temperature was reduced by 6°F

- LVGO yield was the same

- LVGO draw temperature increased by 40°F

- Slop make was reduced.

Next, a study was done to determine the cause of the ejector system's poor performance. Our initial theory was improper design. We decided to conduct a detailed survey to find out what was causing the poor ejector performance. Evaluating unit operating data and looking at oil and gas samples from the overhead system revealed some possible problem sources. A slop oil sample from the ejector-system hotwell was taken and tested. Distillation data is shown in Table 1.

The distillation showed that 90% of the material was kerosene and lighter. The light material was either carried over from the atmospheric crude column or formed in the heater by cracking.

Normally, gasoline/kerosene boiling-range material formed in the heater is minimal. The slop-oil rate was much higher than predicted, based on column overhead temperature and measured noncondensible load. Material boiling at temperatures above 450°F should not have been present. The slop-oil analysis indicated the atmospheric tower was not stripping and only a small amount of LVGO was being entrained. We assumed that reducing condensibles to the ejector may reduce column pressure.

An evaluation of the intercondensers was conducted, including installation of block valves to isolate one of the two parallel first-stage ejectors and intercondensers for cleaning without a unit shutdown. The high proportion of non-condensible gases increases the difficulty of achieving low approach temperatures because of the relatively poor heat-transfer coefficient. The cooling-water temperature typically ranged from 74°F to 80°F. This, in conjunction with the exchanger approach temperature limitation, set the first-stage intercondenser pressure. The exchanger approach temperature was about 20°F. The intercondenser performance was adequate.

At low charge rates, the atmospheric tower's furnace was not thermally limited. Therefore, the atmospheric column cutpoint could be increased, lowering the light slop to the vacuum unit. At high charge rates, stripping steam was reduced to the flooding limit on the stripping trays. Light material to the vacuum column increased.

Reducing the light slop oil from the atmospheric column, assuming this caused the high condensibles load, required modification to the atmospheric column stripping section. The vacuum column light slop oil material is a result of either poor stripping in the atmospheric crude tower or cracking in the furnace. However, furnace cracking was assumed to be negligible.

Further analysis showed that the atmospheric tower stripping section was inadequately designed. Adequate stripping steam at high crude charge rates was not possible. The trays were hydraulically limited and flooded. Introducing appreciable quantities of steam resulted in black diesel oil. Tray modifications were planned during an atmospheric crude unit shutdown.

By modifying the stripping trays and improving stripping efficiency, slop-oil make was reduced, even at higher crude throughputs. Result: a vacuum tower overhead pressure that varied between 3 mmHg to 4.5 mmHg depending on ambient temperature and humidity. Cooling-water temperature to the first-stage ejector intercondensers and LVGO pumparound return temperature became the major factors in minimizing vacuum-column top pressure. A hydraulically-limited stripping section is not a typical refinery problem. But, an inefficient or damaged stripping section is common. When operating at low column pressure, the impact of atmospheric-column stripping-section operating inefficiencies results in significant gas-oil yield losses due to loss of vacuum.

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