Maximise VGO yield

Fundamental operating principles of vacuum ejectors are discussed, including incidents leading to sudden increases in ejector suction pressure, known as breakthrough. Proper ejector component selection and design can significantly prevent breakthrough and increase VGO yield, while reducing resid production

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Good vacuum unit performance is critical with crude oil and asphalt price differentials as high as $20–25 per barrel. For a moderately sized vacuum unit, poor performance can easily increase vacuum residue production by 1 000bpd, resulting in profit loss as high as $8–9MM/yr. Unreliable vacuum ejector system performance is often the root cause of the lost profits. Because ejector systems continue to be plagued with design problems during revamps, more effort needs to be directed at the proper selection and design of the system components. Avoiding these design mistakes begins with understanding fundamental operating principles.

Maintaining VGO product yield

Maintaining vacuum gas oil (VGO) product yield throughout the year requires minimum flash zone pressure and maximum temperature. Operating pressure and temperature determine gas oil product yield for a given feedstock quality assuming heater coil steam rate and stripping section performance are constant. Flash zone temperature is set by heater outlet temperature and pressure. Flash zone operating pressure is controlled by first stage ejector suction pressure and it should be minimised throughout the year to minimise vacuum residue yield. In many cases, higher pressure operation which often occurs during the summer is caused by poor ejector system performance.

Ejector system fundamentals

Typically, the first stage ejector suction pressure changes in a predictable manner with gas load based on the ejector performance curve (Figure 1). First stage ejector gas load comes from process steam, cracked gas, condensable hydrocarbons, and air leakage. Air leakage is generally minimal. Cracked gas is generated in the heater with the amount dependent on heater design, oil stability and operating temperature. Condensable hydrocarbon rate is primarily a function of upstream crude column residue stripping section operation and vacuum column top temperature. Poor crude column stripping increases 300–700°F boiling range hydrocarbons in the vacuum unit feed, which raises ejector condensable hydrocarbon load. Process steam is the largest first stage ejector gas load when coil and stripping steam is used. In a dry vacuum unit where no coil or stripping steam is used, cracked gas is the largest source of first stage ejector load.

First stage ejector gas load normally sets operating pressure. But when first stage ejector operation breaks, it no longer operates on its curve. Breaking is characterised by an abrupt increase in suction pressure. When breaking occurs, vacuum column flash zone pressure rises rapidly, causing VGO product yield to drop and residue production to increase. The yield loss is dependent on the increase in flash zone operating pressure. It is not unusual for ejector breaking to raise pressure by 10–50mmHg.

Steam-jet ejectors use motive steam energy to compress the process gas from the column pressure to the non-condensable gas outlet pressure. The main ejector system components are the ejector and the inter-condenser (Figure 2).

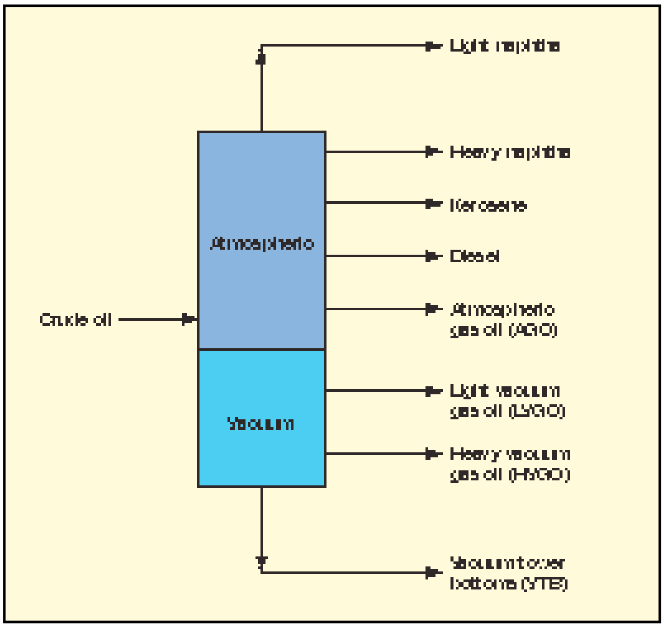

***Figure 1** First Stage Ejector Curve*

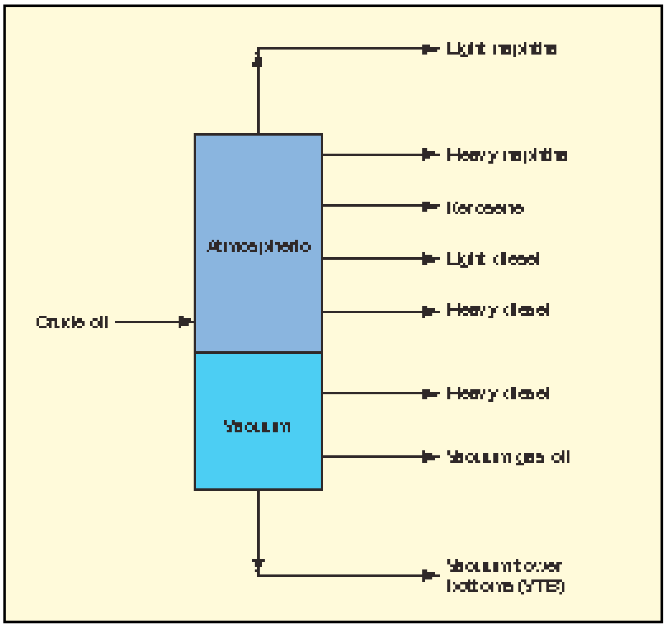

***Figure 1** Main Ejector System Components*

While the ejector is composed of many parts (diffuser, steam chest, steam nozzle), it is the steam nozzle that is the focus of the following discussion.

Inter-condenser and steam nozzles are the most common causes of ejector system problems. First stage inter-condenser operation largely determines the first stage ejector discharge pressure if the second stage ejector is operating properly. As long as the first stage discharge pressure is below the maximum discharge pressure (MDP) then first stage ejector process gas load determines suction pressure. First stage ejector discharge pressure has no influence on column operating pressure as long as it is below MDP.

Steam nozzle motive steam flow rate also impacts on suction pressure and MDP. Lowering steam rate reduces MDP because there is less energy (steam) to compress the process gas, resulting in lower MDP. Increasing steam rate above design raises condensing load and inter-condenser pressure drop, which increases ejector discharge pressure. Therefore, maintaining design steam rate is critical.

Steam ejectors convert pressure energy of the motive steam into velocity. For a critical flow ejector, motive steam enters the steam chest through the steam nozzle at velocities typically in the range of Mach 3–4. Localised pressure inside the steam chest drops slightly below suction pressure so the process gas flows into the steam chest from the suction piping. The mixture (motive steam and process gas) then enters the diffuser. The diffuser consists of converging (narrowing) section, throat (straight piece of pipe), and diverging (widening) section. The shape of the diffuser allows the mixture velocity to exceed Mach 1, whereas in a straight pipe it cannot.

In the converging section of the diffuser process gas is accelerated above Mach 1 and the motive steam velocity drops. Motive energy is transferred to the process gas, and the fluids begin to mix. Pressure rises across the converging section. Motive steam and process gas finally reach the same velocity towards the end of the converging section. If the ejector discharge pressure is below its MDP, then the mixture enters the throat (straight pipe) above Mach 1. Because compressible fluid flow in a straight pipe cannot exceed sonic velocity, there is a sonic shock wave inside the throat where velocity drops below Mach 1. Across the sonic shock wave (sonic boost), the mixture pressure rises sharply. In the diverging section, velocity decreases as the nozzle opening gets wider, thus kinetic energy is converted to pressure. The majority of the ejector's compression ratio occurs from the sonic shock wave.

Almost all refineries' first stage ejectors are designed at high compression ratios. Consequently, suction pressure is determined solely by gas load as long as the discharge pressure is below MDP for the first stage ejector. However, when the first stage ejector discharge operating pressure exceeds MDP, the ejector breaks and vacuum column operating pressure increases.

Steam nozzles

The steam nozzle design and steam specific volume control the amount of motive steam to the ejector. The steam nozzle design is set by the ejector manufacturer based on the information provided during the design and selection process. Once the steam nozzle is installed the actual steam rate to the nozzle is controlled by steam pressure and the amount of superheat. Most refinery ejectors use saturated steam. Therefore, steam pressure is the sole determinant of steam flow. In cases where the nozzles are designed for superheat, maintaining steam temperature and steam pressure is essential. Steam temperature variations can cause fluctuations in motive steam flow rate if motive steam pressure is not controlled. Because total ejector steam flow is normally metered, the actual steam rate can easily be compared to design. Ultimately, steam nozzle motive steam flow rate must be controlled.

First stage ejector inter-condensers

First stage inter-condenser design and operating problems are the most common cause of reduced VGO product yield. The inter-condenser must condense process steam, motive steam and the condensable hydrocarbons. However, most of the duty results from steam condensation, not hydrocarbon condensation. Steam that is not condensed increases gas load to the second stage ejector causing higher first stage ejector discharge pressure. Since inter-condenser duty determines both gas outlet temperature and second stage ejector gas load, it controls first stage ejector discharge pressure and is a critical component of the ejector system. The first stage inter-condenser is typically designed for low pressure drop (5–15mmHg) and must be designed to drain the condensate.

While poor inter-condenser performance can be caused by plugged condensate drains and fouling from amine salts and corrosion by-products, inter-condenser bundle design errors are increasingly causing ejector breaking. This is more prevalent when non-specialised bundle designs are used. Design errors increase pressure drop and raise first stage ejector discharge pressure. Condensate accumulation is the most common cause of problems. Condensate accumulation reduces condensing surface area, raising first stage ejector discharge pressure. If operating pressure remains below MDP, suction pressure will not be impacted. However, when operating pressure reaches MDP, the ejector begins to surge with operation eventually breaking. Breaking significantly increases ejector suction pressure.

Because the first stage ejector and inter-condenser represent a large portion of the entire vacuum system installed cost, they are sized competitively. Furthermore, design motive steam rate is a significant portion of the inter-condenser duty; hence it is often minimised to further reduce cost. This practice leads to low design MDP and little or no margin for error.

Flooded first stage inter-condensers

Condensate tubes become submerged whenever inter-condensers have trouble draining. The submerged tubes reduce the effective surface area available for condensation. Equation 1 shows that when the exchanger surface area for condensation decreases the exchanger LMTD must increase, or the duty must decrease. Higher first stage ejector discharge pressure raises the condensing temperature, thus raising LMTD that helps overcome surface area loss from condensate flooding. Yet, once the ejector discharge pressure increases above its MDP, the ejector operation breaks.

$$Q = U * A * LMTD$$

Equation (1)

$Q = Btu/h$	Exchanger duty
$U = Btu/h\text{-}ft^2\text{-}°F$	Heat transfer coefficient
$A = ft^2$	Exchanger surface area
$LMTD = °F$	Log mean temperature difference

Case study

Plugged dip legs and fouling can cause inter-condenser problems. However, it is poor bundle design that is often the cause of flooded inter-condensers. The first stage inter-condenser must provide heat transfer at very low-pressure drop. Special bundle designs are needed to achieve heat transfer at very low pressure drops. Two common inter-condenser heat exchanger shell types are the E- and X- shells. Two case studies are reviewed that demonstrate how small errors in inter-condenser bundle design can result in high-pressure drop and lost profits.

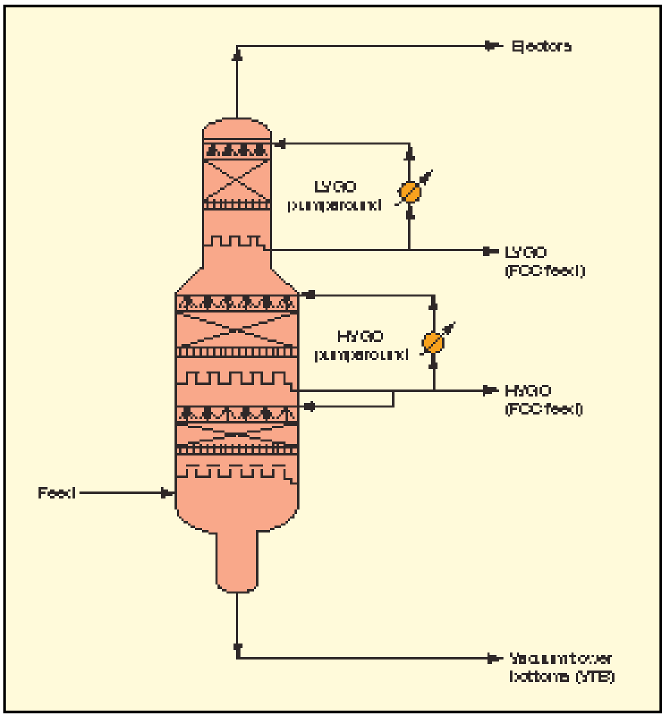

Figure 3 *First-stage Inter-condenser – X-Type Shell*

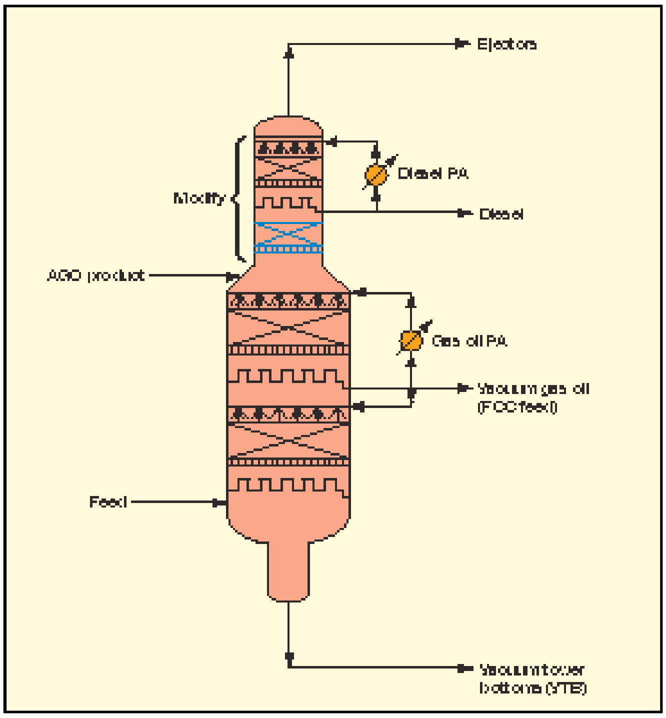

Figure 4 *First-stage Inter-condenser – Baffles*

Case 1: X-shell

Typically, an X-type inter-condenser shell contains a longitudinal L-shaped baffle in addition to vertical baffles. Vapour enters the exchanger and spreads along the length of the bundle. It then enters the bundle where a portion of it condenses and falls to the bottom. The remaining non-condensible vapours pass underneath the longitudinal baffle en route to the outlet nozzle. This type of design forces all of the non-condensibles to flow through the entire bundle before they exit (Figures 3 & 4).

In Case 1, a new inter-condenser X-type shell was installed. Immediately after the exchanger was commissioned, the pressure drop was 25mmHg higher than design. The high pressure drop was causing the first stage ejector to break. Vacuum column pressure was significantly higher and HVGO yield suffered. Upon detailed review, it was determined that the exchanger bundle had problems with the longitudinal baffle design. The baffle included too much tube area (Figure 5) and resulted in higher than design pressure drop.

Case 2: E-shell

A vacuum column overhead system was modified as part of a unit revamp. The existing three-stage vacuum system was converted to a four-stage system. The existing ejectors (all three stages) and second- and third-stage condensers were replaced. A fourth-stage ejector and after-condenser were also added. The existing first stage inter-condenser was re-used. After the unit started up, the vacuum column top pressure was 15–20mmHg higher than design.

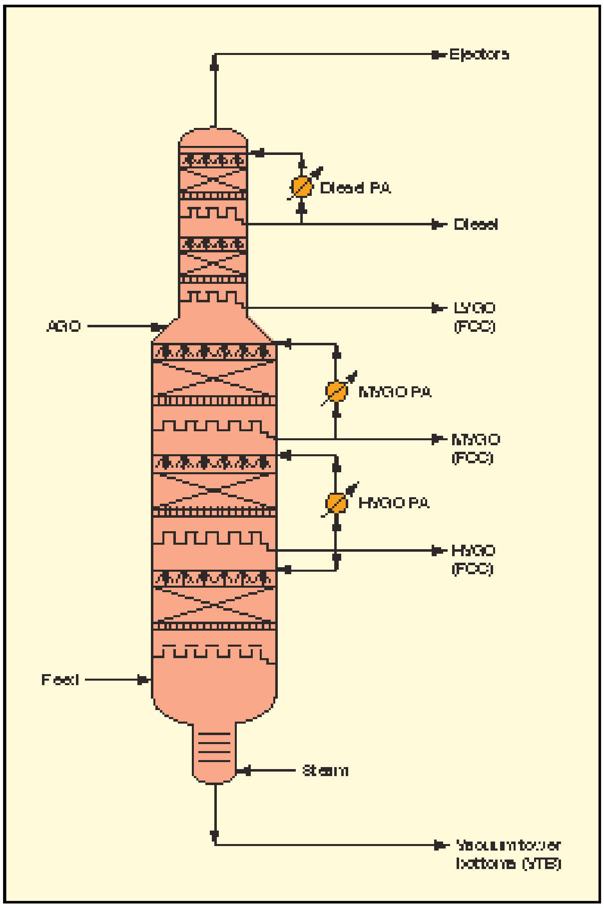

Figure 5 *First-stage Inter-condenser – Longitudinal Baffle*

The first stage inter-condenser bundle was a TEMA E-shell with both vertical and horizontal baffles (Figure 6). The ejector discharge enters at one end of the exchanger, condensate drains toward the middle and the gas outlet is located at the opposite end from the inlet. The exchanger baffles between the condensate drain and the inlet nozzle are vertical baffles. The opening (cut) is vertical. This allows condensate to freely drain along the bottom of the bundle. In theory, most of the condensation occurs in this section of the exchanger and the condensate is removed through the drain. However, as more process steam is added some of the steam condenses downstream from the drain. The baffles between the condensate drain and the outlet nozzle are cut horizontally. This section of the condenser is designed to sub cool the non-condensable vapours before they enter the inlet of the second stage ejector. Only a small amount of hydrocarbon or steam condensate should be present because it must drain through a small hole at the bottom of each baffle. If the amount of condensate exceeds the drain hole's capacity or the hole becomes plugged, condensate builds up, reducing exchanger

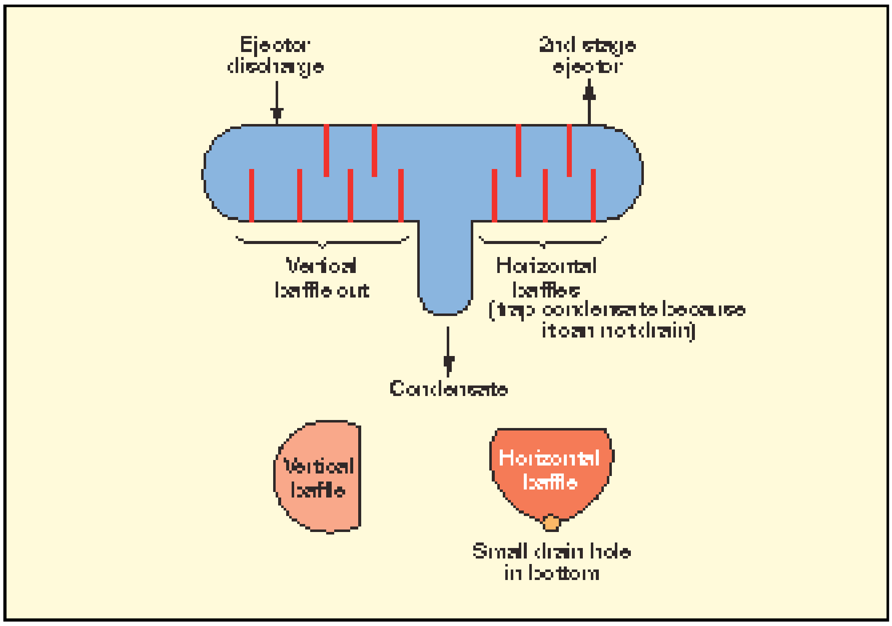

Figure 6 *First stage Inter-condenser – horizontal baffles*

surface area. In the worst-case scenario, condensate is carried into the second-stage ejector, reducing its capacity and further raising first-stage ejector discharge pressure.

The exchanger pressure drop was 18–25mmHg compared to a 6mmHg design. The higher pressure drop was exceeding the MDP of the first-stage ejector resulting in higher vacuum column top pressure. The vapour outlet to the second-stage ejector was cold, as was the entire body of the second-stage ejector. Water was not draining and being entrained to the second-stage ejector. The design vacuum column pressure was achieved only after the condenser was replaced with an X-type design.

The first stage inter-condensers must achieve heat transfer at a very low pressure drop. Ejector manufactures have developed proprietary designs to achieve the competing objectives of low pressure drop and heat transfer. One of the difficulties in identifying inter-condenser problems is that the ejector manufacturers do not supply bundle drawings to protect their know-how and prevent the bundles from being manufactured in local fabrication shops. However, it is essential that the end-user understands the importance of the inter-condenser design as it relates to the ejector MPD and the basic fundamentals of the inter-condenser design. Seemingly small design errors can result in millions of dollars of lost profits due to reduced gas oil product yield.

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