Refinery vacuum unit pressure control is essential to meeting crude unit revamp profitability objectives. While minimum vacuum unit operating pressure always increases the heaviest distillate product yield, low pressure operation is not always the optimum to meet the feedstock quality and rate targets of downstream units. Low operating pressure can cause massive entrainment of vacuum tower bottoms (VTB) into the heaviest distillate product if the column diameter is too small.

Often, optimum vacuum unit operation requires higher column operating pressure, which must be offset by increasing the heater outlet temperature. This maximises the heaviest distillate product yield while avoiding high VTB entrainment.

Vacuum distillate quality must be monitored and controlled; otherwise, downstream unit performance suffers. The higher the VTB contaminants level, the lower the quantity of entrainment that can be tolerated before the downstream unit is affected. VTB quality is crude-dependent; it is not uncommon to have vanadium and nickel levels greater than 500 wt/ppm and 26–28 wt% carbon residue with heavy crude oils. Small amounts of entrained VTB, when processing Maya and Venezuelan crude oils, will dramatically increase the metals and carbon residue in the heaviest distillate product. Some revamps have produced heavy vacuum gasoil (HVGO) products with carbon residue of 1.5 wt% or higher and 30–40 wt/ppm nickel and vanadium.

Pressure control is necessary when the column diameter is the primary unit limit, which often is the case when a unit is revamped. The three main causes of poor pressure control are:

— No means to control pressure
— Fundamental errors in the pressure control system design
— Poor ejector spillback piping design and installation.

Numerous equipment problems can cause variations in distillate yield and quality [Golden S W, Troubleshooting vacuum unit revamps; Petroleum Technology Quarterly, Summer 1998]. However, the focus of this article is controlling column flash zone pressure through the design and operation of the first stage ejector pressure control system.

**Product yield and quality**

Vacuum unit distillate must meet both yield and contaminants specification targets. Refinery vacuum units produce feedstocks for further processing in an FCC, hydrotreater, or lube oil facility (Figures 1 and 2). Maximum, on-specification lube distillate or HVGO product yield occurs when the vacuum column is operated at an optimum flash zone temperature and pressure.

The fired heater, column diameter, heat removal, and/or vacuum ejector system determine the minimum flash zone pressure and optimum temperature. The specific unit equipment limit will determine the optimum combination of temperature and pressure to meet distillate yield and quality targets. If the column diameter is the major limit, then inadequate pressure control often results in high metals, microcarbon residue (MCR), and/or asphaltenes in the distillate products from VTB entrainment.

Vacuum column flash zone pressure and temperature management is the key to maximising profitability. Flash zone temperature and pressure determine the vacuum distillate yield and quality. Whether temperature, pressure, or both, are adjusted depends on specific equipment constraints. The interdependencies of the major equipment complicate this optimisation. For instance, the vacuum unit heater outlet temperature sets the flash zone temperature and it largely determines the cracked gas load on the vacuum ejectors. The maximum

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**Figure 1** Simplified lube vacuum unit process flow

**Figure 2** Simplified fuels vacuum unit process flow
heater outlet temperature, assuming no ejector system limit, is set by the coke laydown rate in the radiant section coils.

High coke formation rates will reduce run length and require heater decoking, as well as increase the cracked gas production. The impact of cracked gas on the column operating pressure depends on whether the unit uses coil or stripping steam. Typically, the operating pressure of a dry vacuum column is more dependent on cracked gas production than a unit using steam, because the cracked gas rate is the primary ejector load on a dry unit. If the column diameter is the limit, then operating pressure will set the VTB entrainment level.

Vacuum distillate yield is affected by pressure and temperature changes. Increasing the column flash zone temperature at a fixed pressure will increase the yield of the heaviest lube cut, or the HVGO. When the temperature is increased at a fixed pressure, the vacuum column capacity factor increases by the ratio of the distillate rate increase. For instance, increasing total vacuum distillate production by 5 per cent will increase the column capacity factor by about 5 per cent.

The capacity factor is derived from Stoke’s Law and is a function of the superficial vapour velocity and vapour density. Flash zone operating temperature has very little effect on the vapour density. Conversely, lower operating pressure can significantly increase the capacity factor. Lower pressure reduces the vapour density, which in turn, increases the superficial vapour velocity. The net effect is always an increase in the column capacity factor.

Due to the effect of pressure on capacity factor, it is possible to reduce the column operating pressure to the point where massive VTB entrainment occurs. High distillate metals and carbon residue will require operating changes to reduce entrainment. Flash zone temperature and/or pressure must be optimised.

Many vacuum units have no pressure control; therefore, the vacuum ejectors set the flash zone operating pressure. Higher ejector gas load increases operating pressure, while lower gas load decreases operating pressure. Once the column exceeds its capacity limit, operating changes must be made. Heater outlet temperature is the only operating variable that can be used when no pressure control exists.

Reducing the operating temperature may reduce the capacity factor. However, the lower heater outlet temperature will also make less cracked gas, which will reduce the ejector load and lower the column operating pressure further.

In some cases, reducing heater outlet temperature actually increases the VTB entrainment because the column pressure decreases as less cracked gas is produced. Lower flash zone pressure increases the column capacity factor and VTB entrainment. This can occur even at reduced distillate product yields.

Pressure control is essential when the vacuum column diameter is the limit. When the heavy distillate product has the appearance of clean motor oil, ie low concarbon and metals, the vacuum column diameter is not limiting product yield. When the column diameter is the limit, the HVGO product is dark or black. As the flash zone capacity factor increases, the VTB entrainment increases.

For a fixed distillate yield (constant VTB yield), the capacity factor increases as the flash zone pressure is reduced. At flash zone capacity factors above 0.36, VTB entrainment begins to increase. The lower the column operating pressure, the larger the effect of small pressure changes on the column capacity factor. Optimisation of flash zone pressure and temperature is required to maximise distillate product yield without exceeding the column diameter limit.

Vacuum unit limit

One of the most frequently asked questions is: “What is the maximum capacity factor at which we can operate our vacuum unit without having problems?” The answer depends on the crude oil being processed and the equipment design. The metals and carbon residue in the heavy distillate product result from entrainment of VTB and volatile metals in the boiling range of a given product.

Volatile metals are always present; however, the quantity is crude oil and gas oil cutoff point dependent [Golden SW and Martin GR, Revamping vacuum units for HVGO quality and cutpoint; NPRA annual meeting, San Antonio, Texas, 17-19 March 1993].

When processing heavy crude oils like Maya or heavy Venezuelan blends, volatile metals can limit HVGO product yields without VTB entrainment. However, once the heavy distillate product goes from an ASTM D1500 colour of 4-6 (orange to green) to 8+ colour (black), then entrainment is the culprit no matter what crude is being processed.

When the maximum capacity factor is exceeded, the heavy distillate product contaminants will increase. Vacuum column capacity is limited by some maximum vapour velocity as measured by the capacity factor, Cf. At very high VTB entrainment, the heavy distillate yield will increase. There will be a step change in the distillate product carbon residue and/or metals for a small change in heavy distillate product yield.

Vacuum unit transfer line and column flash zone and wash section internals design will affect the maximum column capacity. Flash zone internals vary in design and their impact on entrainment is well documented. Wash zone efficiency sets the maximum vapour velocity in the column for a given flash zone design. Higher efficiency internals permit higher capacity factors. However, exceeding the column capacity limit will cause poor gas oil quality no matter what type of internals are installed.

Ultimately, entrainment of VTB is caused by equipment design and a high column capacity factor. The calculation of the column capacity factor, Cc, is as follows:

\[
C_c = \frac{V_s}{\sqrt{\frac{\rho_l}{\rho_v}}} - \frac{P_t - P_v}{P_t}
\]

where,

- \(V_s\) = Superficial vapour velocity, fps
- \(\rho_l\) = Density of vapour, lb/ft³
- \(\rho_v\) = Density of liquid, lb/ft³

Understanding how the flash zone operating pressure affects Cc is important. The capacity factor is a function of superficial vapour velocity and vapour density. The liquid density in a vacuum column wash zone does not change significantly with operating pressure. However, column operating pressure will change both the superficial vapour velocity and the vapour density. Therefore, the vacuum column first stage ejector suction pressure is an important operating variable because it sets the column flash zone pressure.

For a fixed yield of vacuum distillates and VTB, the flash zone capacity factor will increase as the operating pressure is reduced. The lower the flash zone operating pressure, the larger the impact of small pressure changes on Cc.

The heat input to the vacuum unit is typically set by a controller that maintains the temperature somewhere in the transfer line. Therefore, feed heat input is largely fixed unless transfer line temperature changes are made. At low operating pressures, column Cc increases rapidly as the pressure is reduced. At a constant heater outlet temperature and 8mmHgA flash zone pressure, a 1mmHg pressure reduction will increase the Cc by approximately 10 per cent. Whereas a 1mmHg pressure reduction at 20mmHgA flash zone pressure will increase Cc by only 2 per cent. Thus, the lower the column operating pressure the more important it is to have stable pressure control. Vacuum units that operate with no steam in the heater passes and no stripping steam (dry units) typically operate with flash zone pressures between 10 and 20mmHgA absolute.
pressure. A high vacuum column $C_f$ causes high VTB entrainment and contaminates the heavy distillate product. The quantity of entrainment increases rapidly as the $C_f$ increases and this increase does not change linearly with $C_f$. Also, the impact of entrainment on distillate product quality is crude contaminants dependent. For example, if the flash zone pressure is 8mmHgA and the $C_f$ is 0.42, a pressure swing from 8 to 7mmHgA will increase the $C_f$ from 0.42 to 0.46. This will cause massive entrainment.

The effect of entrainment will be a function of the crude source. North Sea crude VTB will have 50-70 wt/ppm metals, whereas Venezuelan medium heavy BCF crude VTB metals will be greater than 800 wt/ppm. Alternatively, if the column is operating at a 20mmHgA pressure and a 0.42 $C_f$, a pressure swing from 20 to 19mmHgA will result in an increase from 0.42 to 0.43 $C_f$. Entrainment will increase; however, distillate quality may not change significantly.

The lower the operating pressure, the greater the sensitivity to small pressure changes. However, the effect of high $C_f$ on distillate quality will be crude source dependent. Ultimately, there is no simple answer to what maximum $C_f$ a vacuum column can be operated at before product quality degrades and profitability drops.

**Ejector operating pressure**

Understanding how the vacuum ejector system operates is essential to understanding how a good pressure control system should be designed [Martin G R, Understanding real-world problems of vacuum ejector performance; Hydrocarbon Processing, Nov 1997].

Vacuum ejectors are a form of a thermal compressor. The motive steam compresses the suction gas to the ejector discharge pressure. The ejector discharge pressure is largely a function of the downstream ejector suction pressure and the intercondenser operation. However, ejector discharge pressure does not affect suction pressure as long as the ejector discharge pressure is below the maximum discharge pressure (MDP) of the ejector. Therefore, the suction pressure of an ejector is determined by the gas load. The higher the gas load, the higher the absolute pressure at the suction of the ejector. The lower the gas load, the lower the operating pressure. Therefore, the first stage ejector gas load sets the vacuum column operating pressure.

Figure 3 shows a first stage ejector for a vacuum unit operating with steam in the heater passes.

Column flash zone pressure is set by the first stage ejector gas load as long as the discharge pressure is below the MDP. The first stage ejector gas load consists of the following:

- Steam (coil/striping steam, saturate water in feed, leaking steam/water)
- Non-condensable gas (cracked gas, air leakage, instrument purge gas, startup fuel gas leakage etc)
- Condensable hydrocarbon.

Ejector load will depend on the process design of the vacuum unit. Often, steam is used to reduce the oil residence time in the heater, lower the oil partial pressure in the flash zone, or strip VTB [Martin G R, Heat-flux imbalances in fired heaters cause operating problems; Hydrocarbon Processing, May 1998].

Cracked gas rates will vary from low production for a well-designed heater with low residence time, to very high when significant oil thermal cracking occurs. Air leakage depends on the size of the unit and is a function of column pressure, number of flanges, and the flange tightness. Condensable oil hydrocarbon rate is set by the feed composition, column overhead temperature, and the steam/cracked gas rate. The higher the steam/cracked gas rate, the higher the condensables load.

Operating with coil steam and/or stripping steam significantly increases the size of the ejectors. Table 1 shows the first stage ejector design loads for a dry vacuum unit and a damp unit that uses steam.

The ejector curve shown in Figure 3 is for a damp unit that uses steam in the heater coils. A dry vacuum unit first stage ejector load is primarily non-condensables. However, condensable oil and steam account for 80 per cent of the ejector load on the damp design. Cracked gas is the largest component of the non-condensables and most of the cracked gas is made in the vacuum heater. Air leakage is between 50 and 200lb/hr, assuming normal flange leakage. Therefore, the operating pressure is controlled by the heater operation on a dry unit and the coil/striping steam and condensables on a damp unit, assuming no pressure control.

Understanding the ejector system design gas load and its components and the actual operating gas load helps identify pressure control problems. While Table 1 shows the design cracked gas load, the actual cracked gas load in a refinery is largely unknown and it will vary tremendously with crude type, heater operation, etc.

The first stage ejector suction pressure will be set by the steam and condensable oil rate on a damp unit and cracked gas rate on a dry unit. Therefore, the dry vacuum unit is more likely to have significant first stage suction load variation if there is no pressure control. Refinery vacuum units usually have three ejectors or a combination of ejectors and liquid ring pumps. In our example, we will use a three-stage ejector system. The first stage ejector has an inter-condenser that condenses the condensable oil, coil/striping steam, and motive steam. Therefore, the second and third stage ejector loads

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**Figure 3** Example of first stage ejector performance curve

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**Table 1**

<table>
<thead>
<tr>
<th>Crude port</th>
<th>Dry operation</th>
<th>Damp operation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-condensables</td>
<td>lb/hr % of total</td>
<td>lb/hr % of total</td>
</tr>
<tr>
<td>Condensables</td>
<td>2100 74.2</td>
<td>2100 16.3</td>
</tr>
<tr>
<td>Coil steam</td>
<td>730 25.8</td>
<td>2800 21.7</td>
</tr>
<tr>
<td>Total</td>
<td>2830 100</td>
<td>12900 100</td>
</tr>
</tbody>
</table>
Figure 4 First stage ejector suction pressure

are primarily non-condensibles for either a dry or a damp vacuum unit.

The second and third stage ejector suction pressures, like the first, are controlled by the gas load. However, the gas load is almost 100 per cent non-condensibles, most of which is cracked gas. Increasing the cracked gas production raises the second and third stage ejector suction pressures. Decreasing cracked gas make will lower the suction pressure to both stages. As long as the first stage ejector suction pressure is always set by gas load unless the discharge pressure exceeds the MDP, the first stage suction pressure will be determined by its suction gas load. Vacuum ejector suction pressure is always set by gas load unless the discharge pressure exceeds the MDP. Assuming the ejector is designed correctly and is not damaged, the suction pressure will vary according to the certified ejector curve. However, when an ejector discharge pressure exceeds its MDP, there is not sufficient motive steam to compress the suction gas to the discharge pressure and the ejector goes into a "break" operation. When this happens the ejector suction pressure will make a step change and it will no longer operate on its curve.

Figure 4 shows the first stage suction pressure increasing from about 6mmHgA to 50mmHgA. This breaking operation and suction pressure can increase dramatically.

The fundamental workings of an ejector system will determine the correct pressure control system. Good vacuum unit pressure control will maintain the first stage ejector suction pressure at the lowest pressure without exceeding the maximum capacity factor of the column. The first stage ejector gas flow rate must be held constant even though the gas rate from the top of the vacuum column varies, otherwise column operating pressure will not be constant. Therefore, it is necessary to provide an independent means of controlling first stage ejector gas flow rate.

**Pressure control**

**First stage ejectors**

There are three methods used to control the first stage ejector suction pressure. They are:

- External gas feed into the first stage suction: steam or fuel gas
- Spillback from the first, second, or third stage ejector discharge
- Throttling first stage ejector motive steam pressure

The first two methods vary gas flow rate to the first stage ejector and the last throttles the motive steam. The specific design of the individual ejector stages and the inter-condensers will determine whether these pressure control systems work or cause very erratic system pressure.

First, good pressure control is defined as the ability to maintain the flash zone operating pressure within a 2mmHgA band. While any of these may work for a given ejector system design, there are fundamental problems with all but one of them that may cause very poor pressure control. Throttling motive steam is not recommended as it usually causes erratic pressure changes. Figures 5 and 6 show the two most common methods. Each of these is discussed later. A refinery ejector system is complex because there are three stages in series and often there are parallel stages that further complicate the system performance. The second and third stage ejectors can affect the first stage ejector system performance, as can the parallel ejectors. The vacuum system's components are the ejectors and condensers [Martin G R, Lines J R, Golden S W, Vacuum system, fundamentals; Hydrocarbon Processing, Oct 1994].

Assuming the ejectors/condensers have no mechanical or process problems, then the ejector suction pressure will vary with the gas load unless it is controlled. The ejector consists of a steam nozzle, steam chest, and diffuser. The system performance requires that each component operate within a relatively narrow operating range, otherwise, the first stage ejector suction pressure may be much higher than design.

The design steam rate for the motive steam nozzle is based on the design process gas load. In actual operation, the steam pressure and temperature will control the flow rate of steam to the nozzle. Throttling steam will cause the ejector operation to quickly deviate from its curve. The pressure control system needs to control the first stage ejector gas load without causing the ejector to "break".

The ejector will follow along its performance curve, Figure 3, unless the discharge pressure on the ejector exceeds the MDP for which the ejector is designed. The ejector breaks once the MDP is reached. Breaking occurs when the shock wave moves out of the diffuser section. Breaking increases ejector suction pressure and this increase can be significant.

The performance curve (unbroken operation) shows how the ejector suction pressure increases as the gas load to the ejector increases. First stage ejector inlet pressure and system pressure drop control vacuum column distillate yield for a given vacuum column fired heater outlet condition. Unfortunately, the vacuum unit ejector system first stage gas loads are usually not precisely known. This uncertainty in the process design must be considered when designing the control system.

Figure 5 shows steam or fuel gas being used to control the first stage ejector gas flow rate. An external steam is fed to the first stage ejector inlet. As the process gas load changes from the top of the vacuum column, the external stream rate flow rate is varied by the pressure controller. Whether fuel gas or steam is used, the goal of loading the first stage ejector is achieved. However, the overall impact of fuel gas or steam on the vacuum system is not the same because fuel gas does not condense.

Controlling first stage ejector gas load with steam can adequately control first stage ejector pressure. However, steam also increases the condensing load on the first stage inter-condenser, which raises the inter-condenser gas outlet temperature. Increasing the first stage inter-condenser load will increase the first stage ejector discharge pressure.

Higher inter-condenser outlet tem-
perature will increase the second stage ejector gas load, which raises the second stage ejector suction pressure. As long as the first stage ejector discharge pressure does not exceed its MDP, then this control system will work. However, if the first stage ejector discharge pressure exceeds MDP then there will be a "break" in the first stage suction pressure.

Alternately, controlling first stage ejector load with fuel gas can adequately control pressure. However, fuel gas also increases the second and third stage ejector gas loads along with the first. A higher second stage gas load will increase the first stage ejector discharge pressure. As long as first stage discharge pressure is below MDP, higher second and third stage gas loads will not affect pressure control.

Another potential problem is that higher third stage gas load will increase the third stage ejector suction pressure. As long as the second stage ejector discharge pressure does not exceed its MDP, then increases in third stage ejector gas load will not cause pressure control problems. However, if the second stage ejector breaks, then the first stage discharge pressure will increase. If the first stage discharge pressure exceeds its MDP then it will break and the first stage pressure control will be erratic.

Vacuum unit pressure control with spillback from the first, second, or third stage discharge is also used to control the first stage suction pressure. Figure 6 shows spillback from the third stage discharge to the first. This is common and often it does not work. When spillback is used from either the second or the third stage to the first, it is possible to increase the first stage discharge pressure above its MDP. The results will be similar to using an external source of fuel gas, which "breaks" the second stage ejector.

This increases first stage ejector discharge pressure and can cause breaking operation of the first stage ejector if the MDP is exceeded. Breaking the first stage ejector results in poor pressure control.

Correct pressure control

Good vacuum column pressure control will load the first stage ejector without affecting other parts of the ejector system. A properly designed pressure control system is shown in Figure 7. The first stage gas load is controlled by recycling gas from the first stage ejector discharge to the suction. This design maintains a constant first stage gas load; hence, the inlet pressure can be controlled.

Pressure control of a dry vacuum column is more difficult because the first stage gas load is primarily cracked gas and cracked gas production rate is variable. The damp column first stage ejector load is primarily steam and condensable oil. In the damp column operation, stripping steam and coil steam can be adjusted to load the ejector. Although this will prevent large pressure changes, it will not allow tight control of the flash zone pressure. On a dry vacuum unit, the first stage ejector suction pressure will vary with the cracked gas load.

Cracked gas load changes with crude type and heater operation. Thus, the load to the first stage ejector of a dry vacuum column is more variable and therefore is more likely to have large changes in operating pressure.

A spillback, as shown in Figure 7, is essential for vacuum units where the column is being operated close to the diameter limit. The spillback control valve piping design should be free draining on both sides of the control valve. A common mistake is to install the control valve on a lower platform or deck with vertical piping running back up to the ejector suction line or discharge line.

Assuming a first stage discharge pressure of 65mmHgA and a suction pressure of 8mmHgA, the available pressure drop for the spillback system is 57mmHg, or 2.5ft of water. Steam and hydrocarbon can condense in the line and form a liquid seal that blocks the spillback flow. A free draining system is required.

Operating at high C requires stable pressure control. Good pressure control requires proper instrumen-
tation. The pressure controller should use an absolute pressure transmitter spanned for the specific operating range with appropriate accuracy. In other words, a 0–500mmHgA transmitter range with an accuracy of ±0.25 per cent of span is not adequate when the column is operating at a flash zone pressure of 8mmHgA. A low range absolute pressure transmitter should be used to measure pressure.

**Optimising product yield**

The existing major equipment bottlenecks must be understood to optimise the vacuum unit operating temperature and pressure. The major equipment that control HVGO product yield on a vacuum unit is the heater, vacuum column, and ejector system. Temperature/pressure management is often the key to increasing product yield and maintaining acceptable metals and carbon residue.

For example, a dry vacuum column operating with a flash zone pressure of 9mmHgA, where the column diameter is limiting HVGO yield, will need good pressure/temperature management to optimise yields. In this case, when the heater outlet temperature is increased from 740°F to 760°F, the HVGO product carbon residue increases to over 1 wt%.

Although the heater has ample capacity to push the column feed temperature higher, the column is at the vessel shell capacity limit. The column is operating at its maximum Cf 0.44 with a flash zone pressure of 9mmHgA and a heater outlet temperature of 740°F. Increasing the heater outlet to 760°F increases the Cf above 0.44. The high column capacity factor entrains VTB into the HVGO product. The vacuum column is operating at a capacity limit, but the heater has additional capacity.

Increasing the heater outlet from 760°F to 790°F and raising the flash zone pressure from 9 to 12mmHgA will decrease the Cf from 0.44 to 0.4, while increasing the combined LVGO and HVGO product yield by 7.6 per cent. If a properly designed pressure controller is installed, the operating pressure and temperature can be optimised to meet yield and quality requirements.

**Conclusion**

Properly designed pressure control of vacuum columns is crucial when the column is operated near the diameter limit and product quality must be maintained. If the column operating pressure is lower than expected, the capacity factor may exceed the column diameter limit, and heavy distillate product quality will suffer. Even worse, the column may flood and be inoperable.

Improperly designed pressure control systems will probably not work at all. These systems often cause the column pressure to oscillate and, worst case, cause the ejector system to break. Pressure control is a necessity when operating near the column diameter limit.

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