Vacuum Unit Pressure Control: Impact on Refinery Profitability

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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 off-set by increasing the heater outlet temperature. This maximizes 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 weight ppm and 26-28 weight percent 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 unsuccessful revamps have produced heavy vacuum gas oil (HVGO) products with carbon residue of 1.5 weight percent or higher and 30-40 weight 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

Photo 1 Vacuum Ejector

Numerous equipment problems can cause variations in distillate yield and quality[1]. 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 contaminant specification targets. Refinery vacuum units produce feedstocks for further processing in an FCC, Hydrocracker, 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 asphaltenes in the distillate products from VTB entrainment.

Vacuum column flash zone pressure and temperature management is the key to maximizing 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 optimization. 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 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 and/or stripping steam. Typically, the operating pressure of a dry vacuum column is more dependent on cracked gas produc-

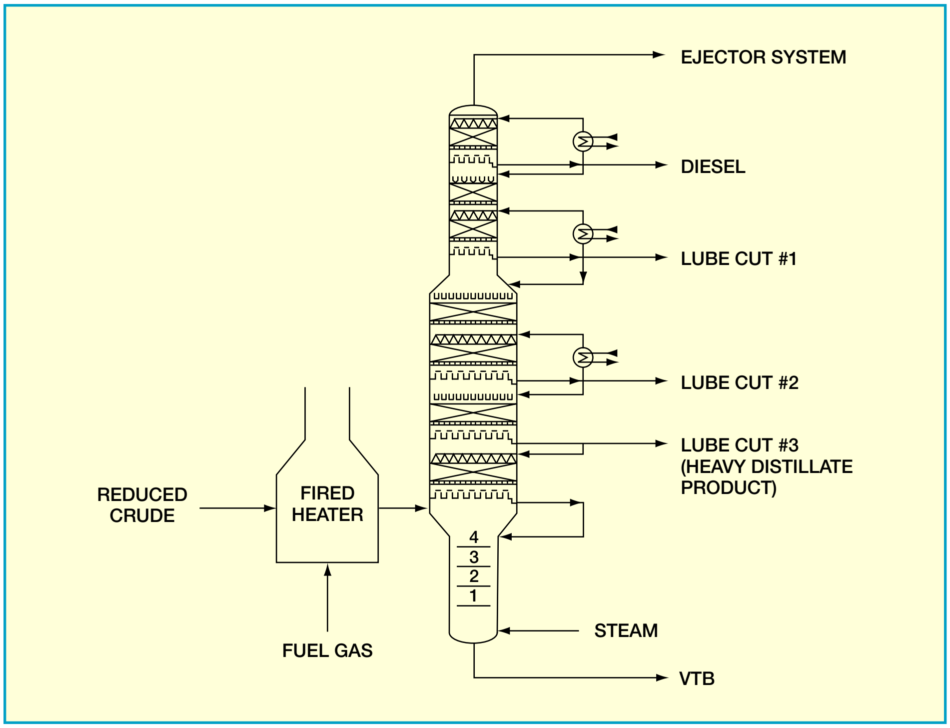

Figure 1 Simplified Lube Vacuum Unit Process Flow Diagram

tion than a unit that uses 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% will increase the column capacity factor by about 5%. The capacity factor is derived from Stoke's Law and is a function of the superficial vapor velocity and vapor density. Flash zone operating temperature has very little effect on the vapor density. Conversely, lower operating pressure can significantly increase the capacity factor. Lower pressure reduces the vapor density, which in turn, increases the superficial vapor 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 optimized.

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, i.e. 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. Optimization of flash zone pressure and temperature is required to maximize distillate product yield without exceeding the column diameter limit.

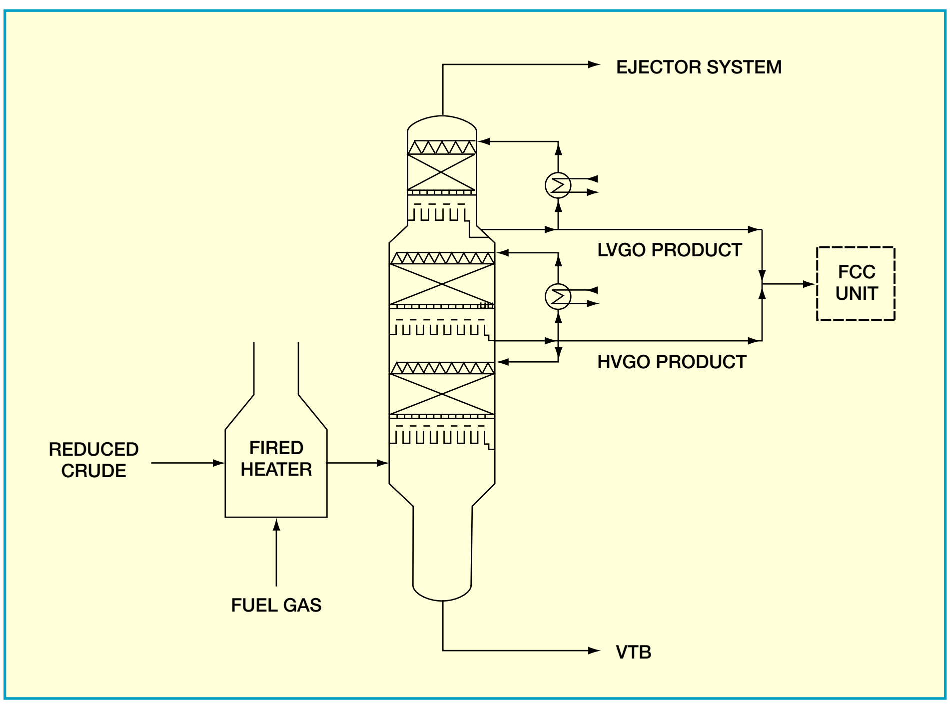

Figure 2 Simplified Fuels Vacuum Unit Process Flow Diagram

Vacuum Unit Limit: Column Diameter

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 cutpoint dependent[2]. 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 color of 4-6 (orange to green) to 8+ color (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 vapor velocity as measured by the capacity factor, C_f. At very high wash zone capacity factors (above 0.4 to 0.44), massive VTB entrainment into the heavy distillate will occur. 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, 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 vapor 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, C_f, is as follows:

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

where, V_s = Superficial Vapor Velocity, ft/sec
ρ_v = Density of Vapor, lb/ft^3
ρ_l = Density of Liquid, lb/ft^3

Understanding how the flash zone operating pressure affects C_f is important. The capacity factor is a function of superficial vapor velocity and vapor 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 vapor velocity and the vapor 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 C_f.

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 C_f increases rapidly as the pressure is reduced. At a constant heater outlet temperature and 8 mmHgA flash zone pressure, a 1 mmHg pressure reduction will increase the C_f by approximately 10%. Whereas, a 1 mmHg pressure reduction at 20 mmHgA flash zone pressure will increase C_f by only 2%. 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 10-20 mmHgA 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 8 mmHgA and the C_f is 0.42, a pressure swing from 8 to 7 mmHgA 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 15-50 weight ppm metals, whereas Venezuelan medium heavy BCF crude VTB metals will be greater than 800 weight ppm. Alternately, if the column is operating at a 20 mmHgA pressure and a 0.42 C_f, a pressure swing from 20 to 19 mmHgA 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 before product quality degrades and profitability drops.

Ejector Inlet Operating Pressure

Understanding how the vacuum ejector system operates is essential to understanding how a good pressure control system should be designed[3]. 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 suc-

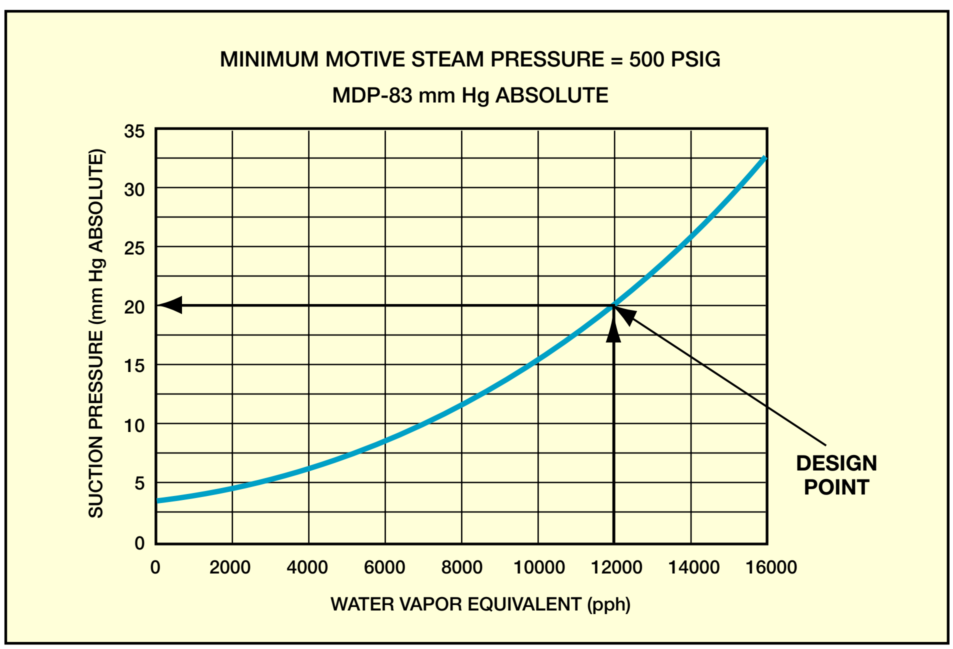

Figure 3 First Stage Ejector Performance Curve Example

tion 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/stripping steam , soluble water in feed, leaking steam/water)
- Non-condensable Gas (cracked gas, air leakage, instrument purge gas, start-up 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. 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[4]. 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 condensable loads.

Operating with coil steam and/or stripping steam significantly increase the size of the ejectors. Table I 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% 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 50-200 lb/hr assuming normal flange leakage. Therefore, the operating pressure is controlled by the heater operation on a dry unit and the coil/stripping steam and condensables on a damp unit, assuming no pressure control.

Understanding the ejector system design gas load and percentage of each component and the actual operating gas load helps identify pressure control problems. While Table I 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/stripping steam, and motive steam. Therefore, the second and third stage ejector loads are primarily non-condensables 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% non-condesables, the majority 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 system discharge pressure is below the MDP, the first stage suction pressure will be determined by its suction gas load, not downstream pressure.

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 6 mmHgA to 50 mmHgA. This is 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 2 mmHgA band. While any of these may work for a given ejector system design, there are fundamental problems with all

First Stage Ejector Design Gas Load

COMPONENT	DRY OPERATION		DAMP OPERATION	
	lb/hr	% of total	lb/hr	% of total
Non-Condensables	2100	74.2	2100	16.3
Condensables	730	25.8	2800	21.7
Coil Steam	0	0	8000	62.0
Total	2830	100	12900	100

Table I

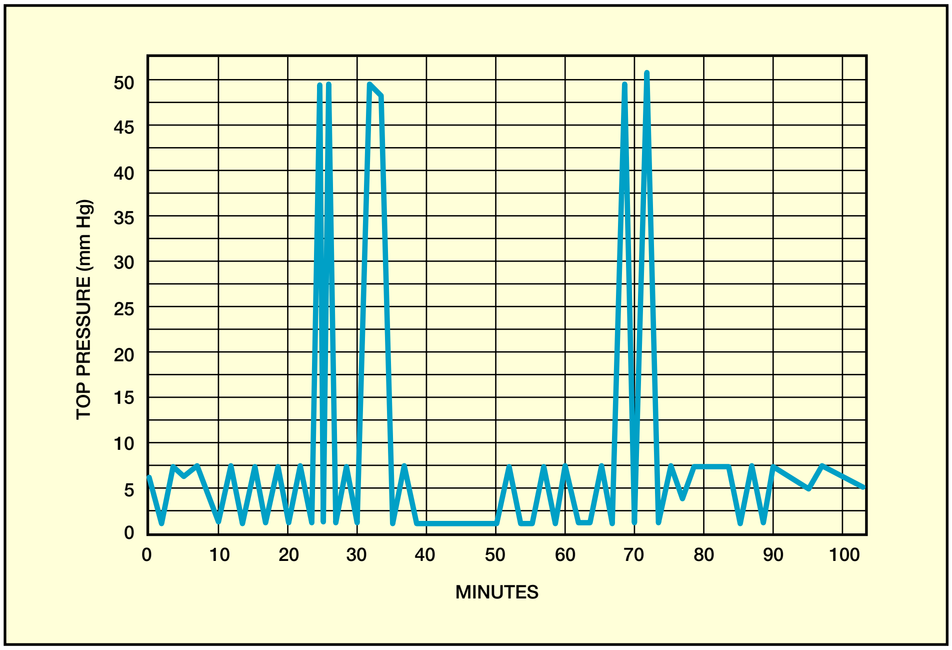

Figure 4 First Stage Ejector Suction Pressure

but one of them that may cause very poor pressure control. Throttling motive steam is not recommended as it almost always causes erratic pressure changes. Figures 5 and 6 show the two most common methods. Each one of these will be discussed.

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[5]. 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

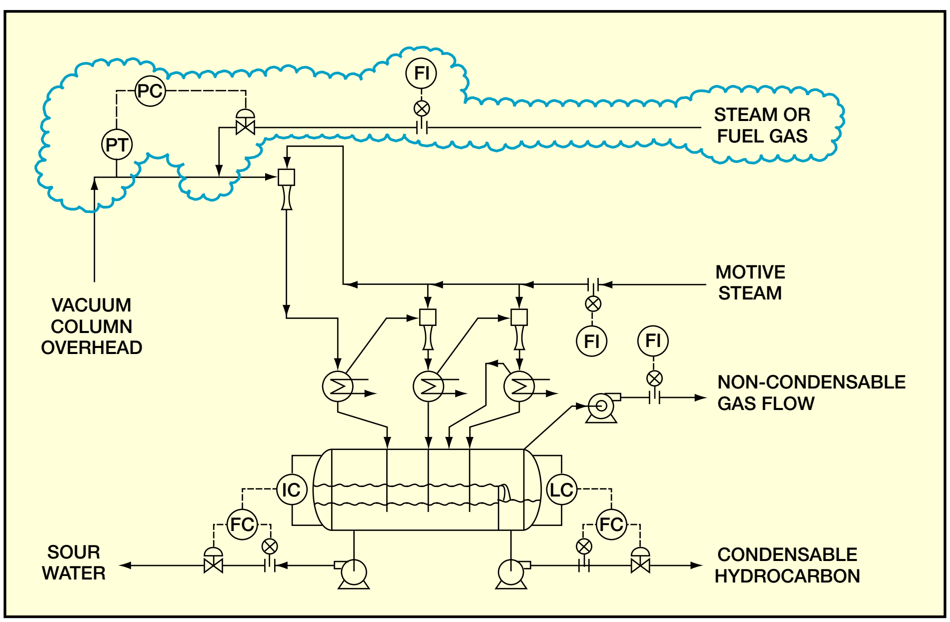

Figure 5 Steam or Fuel Gas into 1st Stage

the ejector to "break".

The ejector will follow along its performance curve, Figure 3, unless the discharge pressure on the ejector exceeds the maximum discharge pressure (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 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 stream is fed to the first stage ejector inlet. As the process gas load changes from the top of the vacuum column, the external stream 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 temperature 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

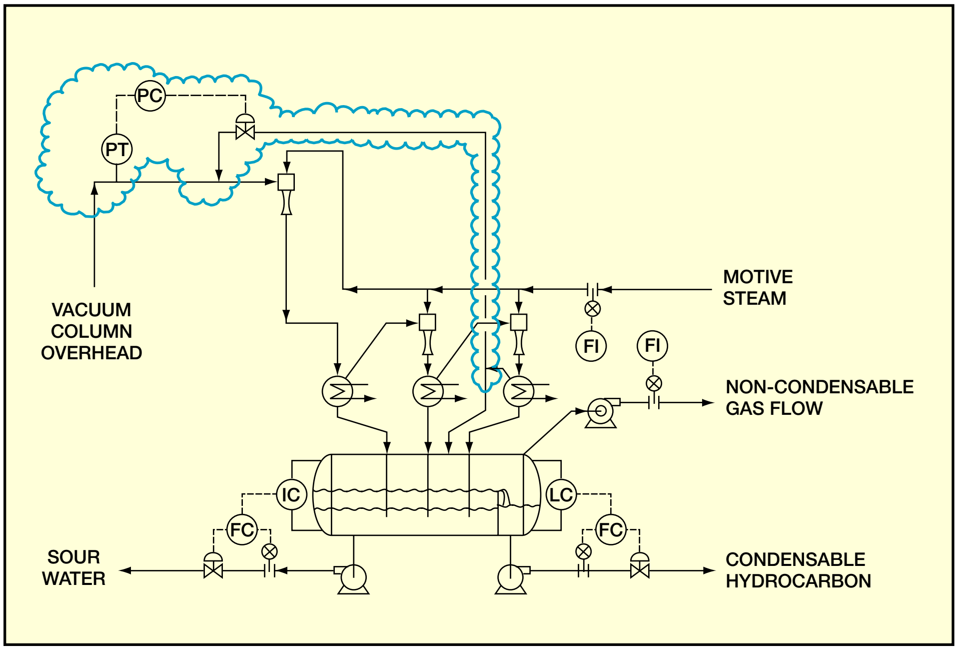

Figure 6 Spillback from 3rd to 1st Stage

ing" operation of the first stage ejector if the MDP is exceeded. "Breaking" the first stage ejector results in poor pressure control.

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 "break-

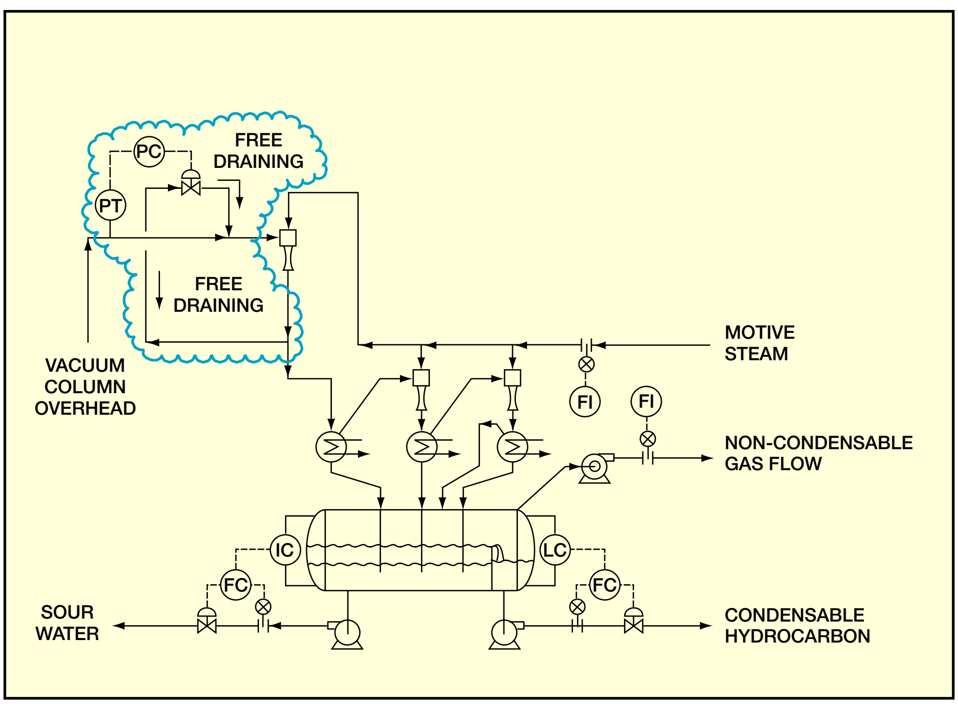

Figure 7 Ejector System with 1st Stage Spillback

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 65 mmHgA and a suction pressure of 8 mmHgA, the available pressure drop for the spillback system is 57 mmHg, or 2.5 ft of water. Steam and hydrocarbon can condense in the line and form a liquid seal that 'blocks' the spillback flow. The spillback system will not work because the available pressure drop cannot overcome the static head of liquid in the spillback line. A free draining system is required.

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

Optimizing Product Yield: Pressure/Temperature

The existing major equipment bottlenecks must be understood to optimize 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 9 mmHgA, where the column diameter is limiting HVGO yield, will need good pressure/temperature management to optimize yields. In this case, when the heater outlet temperature is increased from 740 to 760°F, the HVGO product carbon residue increases to over 1 weight percent. Although the heater has ample capacity to push the column feed temperature higher, the column is at the vessel diameter capacity limit. The column is operating at its maximum C_f 0.44 with a flash zone pressure of 9 mmHgA and a heater outlet temperature of 740°F. Increasing the heater outlet to 760°F increases the C_f 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 to 790°F and raising the flash zone pressure from 9 to 12 mmHgA will decrease the C_f from 0.44 to 0.4, while increasing the combined LVGO and HVGO product yield by 7.6%. If a properly designed pressure controller is installed, the operating pressure and temperature can be optimized to meet yield and quality requirements.

Conclusions

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[6]. Even worse, the column may flood and be inoperable. Improperly designed pressure control systems will likely 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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