Troubleshooting crude vacuum tower overhead ejector systems

Use these guidelines to improve performance and product quality

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Routinely surveying tower overhead vacuum systems can improve performance and product quality. These vacuum systems normally provide reliable and consistent operation. However, process conditions, supplied utilities, corrosion, erosion and fouling all have an impact on ejector system performance.

Refinery vacuum distillation towers use ejector systems to maintain tower top pressure and remove overhead gases (Fig. 1). However, as with virtually all refinery equipment, performance may be affected by a number of variables. These variables may act independently or concurrently. It is important to understand basic operating principles of vacuum systems and how performance is affected by:

- Utilities
- Corrosion and erosion
- Fouling
- Process conditions.

Reputable vacuum-system suppliers have service engineers that will come to a refinery to survey the system and troubleshoot performance or offer suggestions for improvement. A skilled vacuum-system engineer may be needed to diagnose and remedy system problems.

UTILITIES

When a vacuum system is initially designed, utilities are established and the most extreme conditions are usually used for the design basis. Once operating, actual utility supply conditions can be different than those set at the design stage and vary occasionally. Important utilities for ejector systems are motive steam and cooling water. Motive steam pressure, quality and temperature are critical variables. Flowrate and inlet temperature are important for cooling water.

Motive steam conditions. These are very important and have a direct impact on an ejector's operation. If motive steam supply pressure falls below design, then the nozzle will pass less steam. When this happens, the ejector is not provided with enough energy to compress the suction load to the design discharge pressure. The same problem occurs when the supply motive steam temperature rises above its design value. Result: Increased specific volume and, therefore, less steam passes through the nozzle.

Fig. 1. Twin-element, three-stage ejector system on crude vacuum tower.

An ejector may operate unstably if it is not supplied with enough energy to allow compression to its design discharge pressure. If the actual motive steam pressure is below design or its temperature above design, then, within limits, an ejector's nozzle can be rebored to a larger diameter. The larger nozzle diameter allows more steam to flow through and expand across the nozzle. This increases the energy available for compression.

If motive steam supply pressure is more than 10% to 20% above design, then too much steam expands across the nozzle. This tends to choke the diffuser. When this occurs, less suction load is handled by the ejector and vacuum tower top pressure tends to rise. If an increase in tower top pressure is not desired, then ejector nozzles must be replaced with ones with smaller throat diameters.

Steam quality is important. Wet steam can be damaging to an ejector system. Moisture droplets in motive steam lines are accelerated to supersonic velocities and become very erosive. Moisture in motive steam is noticeable when inspecting ejector nozzles. Rapidly accelerated moisture droplets erode nozzle internals. They etch a striated pattern on the nozzle's diverging section and may actually wear out the nozzle mouth. Also, the inlet diffuser tapers and throat will have signs of erosion. The exhaust elbow at the ejector's discharge can erode completely through. Severe tube impingement in the intercondenser can also occur depending upon ejector orientation. To solve wet steam problems, all lines up to the ejector should be well insulated. Also, a steam separator

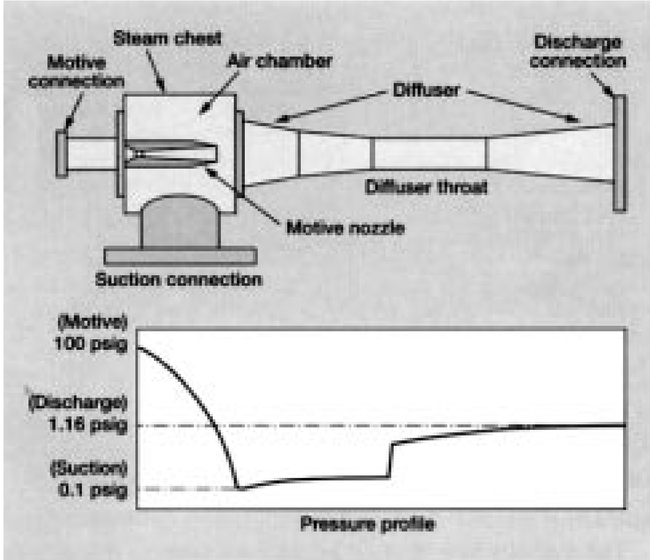

Fig. 2. Ejector components and pressure profile.

with a trap should be installed immediately before an ejector's motive steam inlet connection. In some cases, a steam superheater may be required.

Wet steam can also cause performance problems. When water droplets pass through an ejector nozzle, they decrease the energy available for compression. The effect is a decrease in load handling ability. With extremely wet steam, the ejector may even break operation.

Cooling water. Ejector system intercondensers and intercondensers are designed to condense steam and condensible hydrocarbons, and cool non-condensible gases. This occurs at a pressure corresponding to the preceding ejector's design discharge pressure and the following ejector's design suction pressure. When the cooling water supply temperature rises above its design value, ejector system performance is penalized. A rise in cooling water temperature drives down a condenser's available log-mean temperature difference (LMTD). The condenser does not condense enough and more vapors are carried out with the non-condensible gases as saturation components. A pressure drop increase across the condenser is noticeable. The ejector following this condenser cannot handle the increased load at this pressure. Pressure rises and the preceding ejector does not have enough energy to discharge to the higher pressure. **Result:** The preceding ejector breaks operation and the system may become unstable.

This also occurs if the cooling water flowrate falls below design. At lower-than-design cooling water flowrates, there is a greater water temperature rise across a condenser. This also lowers LMTD and the above situation occurs.

Problems with cooling water normally occur during summer months. This is when the water is at its warmest and demands on refinery equipment are highest. If the cooling water flowrate or temperature is off design then new ejectors or condensers may be required to provide satisfactory operation.

EJECTOR FUNDAMENTALS

The basic operating principle of an ejector is to convert pressure energy into velocity. This occurs with adiabatic expansion of motive steam across a converging/diverging nozzle from motive pressure to suction load operating pressure. Supersonic velocity from the nozzle mouth results. Typically, velocities of mach 3 to 4 are achieved.

In operation, motive steam expands to a pressure below the suction pressure. This creates a driving force to bring the suction load into the ejector. High-velocity motive steam entrains and mixes with the suction load gas. The resulting mixture is still supersonic. As this mixture enters the converging/diverging diffuser, high velocity is reconverted into pressure. A diffuser's converging section reduces velocity as crossflow area is reduced. The diffuser's throat is designed to create a normal shock wave. A dramatic increase in pressure occurs as the flow across the shock wave goes from supersonic to sonic to subsonic after the shock wave. In the diffuser's diverging section, cross-sectional flow area is increased and velocity is further converted to pressure. Fig. 2 details ejector components and a pressure profile for an ejector having a compression ratio in excess of 2:1.

Ejector systems are required to operate over a wide range of conditions—from very light loads to loads above design. An ejector system must stably adapt to all anticipated operating conditions. Determining the design non-condensable and light-end hydrocarbon loading is essential for stable operation. Furthermore, an accurate understanding of system back pressure is important.

Ejector systems may be configured a number of different ways to offer flexibility in handling various feedstocks and differing refinery operations. A single vacuum train with one set of ejectors and condensers has the lowest initial capital cost, but flexibility is limited. Often, parallel ejector trains are installed for each stage. Each parallel ejector will handle a percentage of the total loading. For example:

- Twin element ejectors, each designed for 50% of total load
- Triple element ejectors, each designed for 40% of total loading for 120% capacity
- Twin element, ⅓:⅔ ejector trains
- Other configurations.

Parallel ejector trains allow one train to be shut down for maintenance while the column operates at reduced conditions. Also, at light loadings, a train may be shut down to conserve refinery operating costs. Fig. 3 shows a typical vacuum tower ejector system with a triple element ejector and first intercondenser. The second intercondenser and aftercondenser are a single element.

CORROSION AND EROSION

Corrosion may occur in ejectors, condensers or vacuum piping. Extreme corrosion can cause holes and air leaks into the system. This destroys vacuum system performance.

Erosion may occur within the ejectors. Poor steam quality and high velocities erode diffuser and motive nozzle internals. An ejector manufacturer will provide certified information that gives the motive nozzle and diffuser throat design diameters. If a routine inspection of these parts indicates an increase in cross-sectional area over 7%, then performance may be compromised and replacement parts will be necessary.

Corrosion is a result of improperly selected metallurgy. Ensure that the most appropriate materials are used before replacing parts. A common corrosion problem occurs when carbon steel tubing is used in condensers. Although carbon steel may be suitable for the crude feedstock handled, it is not always the best practical choice. It does offer the initial advantage of lower capital cost. However, operating problems far outweigh modest up-front savings.

Vacuum towers undergo periods of extended shutdown for routine maintenance, revamp or other reasons. During this period, a condenser with carbon steel tubing will be exposed to air and will rust and develop a scale buildup. When the system starts up, the condensers are severely fouled. They will not operate as designed and vacuum system operation is compromised. Modest savings in initial investment for steel tubing is quickly lost with less-than-optimal tower operations due to rusted and scaled tubing. Vacuum system manufacturers often caution against using carbon steel tubing.

Fouling. Intercondensers and aftercondensers are subject to fouling like all other refinery heat exchangers. This may occur on the tubeside, shellside or both. Fouling deters heat transfer and, at some point, may compromise system performance.

Cooling tower water is most often used as the cooling fluid for vacuum condensers. This water is normally on the tubeside. Typical fouling deposits on tubing internals cause a resistance to heat transfer. Over a prolonged period of time, actual fouling may exceed the design value and condenser performance falls short of design.

Vacuum tower overhead gases, vapors and motive steam are normally on the condenser's shellside. Depending on tower fractionation and the type of crude processed, a hydrocarbon film may develop on the tube's outside surface. This film is a resistance to heat transfer, and over time, this fouling will exceed design. Once this occurs, condenser performance falls short.

Routine refinery procedures should include periodic cleaning of condenser bundles. Cleaning procedures must be for the condenser's tubeside and shellside. To facilitate shellside cleaning, a common practice is to specify removable tube bundles (i.e., TEMA designation BXU, AXS or AXT).

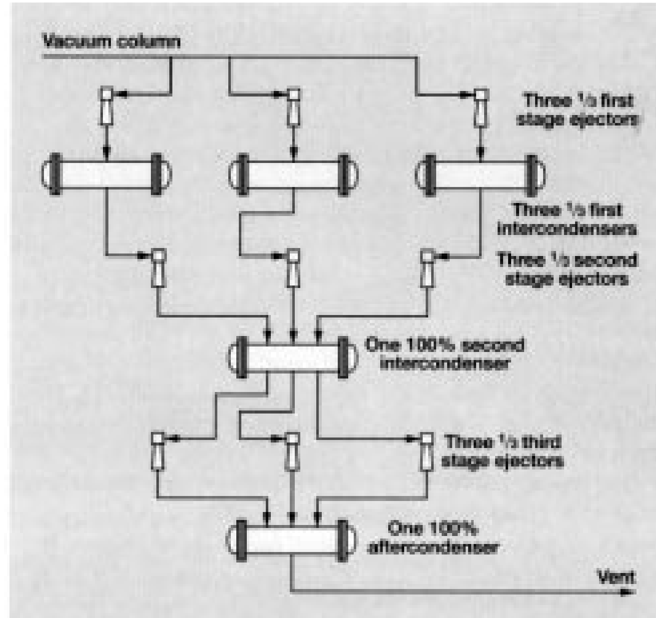

Fig 3. Typical multi-stage system.

Process conditions. These are very important for reliable vacuum system operation. Process conditions used in the design stage are rarely experienced during operation. Vacuum system performance may be affected by the following process condition variables that may act independently or concurrently:

- Non-condensible gas loading, either air leaks or light-end hydrocarbons
- Condensible hydrocarbons
- Vacuum tower loading
- Vacuum system back pressure
- Condenser condensate barometric leg.

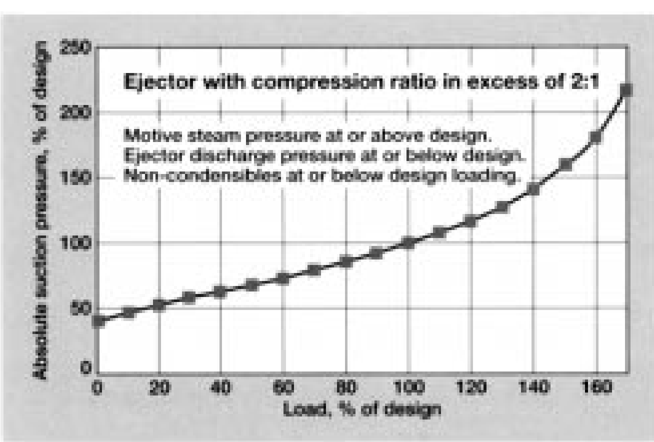

Fig 4. Typical first-stage ejector operating curve.

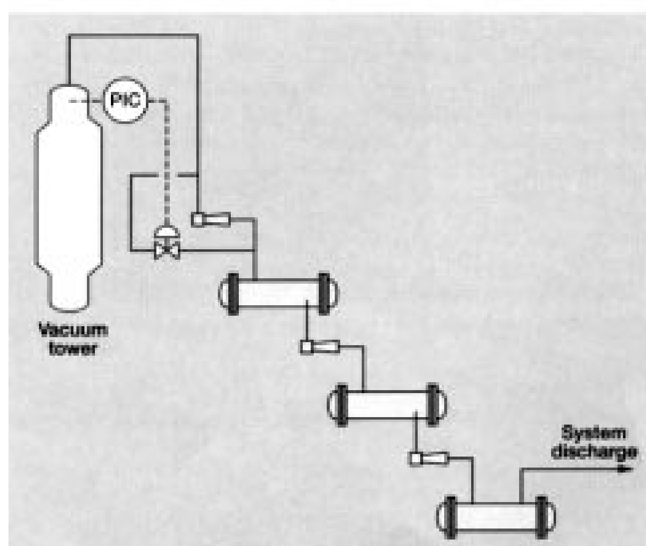

Fig. 5. Preferred recycle control scheme to maintain tower pressure at design when handling overheads below design.

Non-condensible loading. Vacuum systems are susceptible to poor performance when non-condensible loading increases above design. Non-condensible loading to a vacuum system consists of air leaking into the system, light-end hydrocarbons and cracked gases from the fired heater. The impact of higher-than-design non-condensible loading is severe. As non-condensible loading increases, the amount of saturated vapors discharging from the condenser increases. The ejector following a condenser may not handle increased loading at the condenser's design operating pressure. The ejector before the condenser is not designed for a higher discharge pressure. This discontinuity in pressure causes the first ejector to break operation. When this occurs, the system will operate unstably and tower pressure may rapidly rise above design values.

Non-condensible loadings must be accurately stated. If not, any vacuum system is subject to performance shortcomings. If non-condensible loadings are consistently above design, then new ejectors are required. New condensers may be required depending on severity.

Condensible hydrocarbons. Tower overhead loading consists of steam, condensible hydrocarbons and noncondensibles. As different crude oils are processed or refinery operations change, the composition and amount of condensible hydrocarbons handled by the vacuum system vary. A situation may occur where the condensible hydrocarbon loading is so different from design that condenser or ejector performance is adversely affected.

Table 1. Ejector evaluation

Problem	Effect	Corrective action
1. Lower-than-design motive steam pressure.	1. Poor ejector performance.	1. Raise steam pressure or bore steam nozzles.
2. Higher-than-design motive steam pressure.	2. Reduced ejector capacity and wastes steam.	2. Reduce motive pressure or replace steam nozzles with new nozzles designed for a higher steam pressure.
3. Higher-than-design steam temperature (50°F or more).	3. Poor ejector performance.	3. Raise steam pressure or bore steam nozzles.
4. Higher-than-design discharge pressure.	4. Poor ejector performance.	4. Look downstream for problems that could be: a. Condenser problem b. Downstream ejector problem c. Discharge piping restriction.
5. Low ejector discharge temperature. Ejector discharge temperature should be superheated at least 50°F above saturation. If not, the cause is wet motive steam.	5. Reduced ejector capacity or poor performance.	5. a. Insulate steam lines b. Add moisture separator in motive steam line.
6. Higher than design suction pressure (assuming motive steam pressure and quality are normal and discharge pressure is equal to or less than design).	6. Greater-than-design load or mechanical problems with ejector. Either worn out internals or possible internal steam leak around steam nozzle threads.	6. Inspect internal dimensions and replace if necessary. Tighten steam nozzle to steam chest if necessary or seal weld nozzle to steam chest.

Table 2. Condenser evaluation

Problem	Effect	Corrective action
1. High DP across shellside. (As a rule of thumb, normally DP should be 5% of absolute design operating pressure or less).	1. Poor condenser performance: a. Shell side or tubeside fouling b. Cooling water temperature higher than design c. Low cooling water flowrate d. Higher-than-design condensible hydrocarbon (approx. 20% to 30% above design.	1. a. Clean tubes b. Reduce temperature, increase cooling water flow c. Increase cooling water flow d. Reduce hydrocarbon load or larger condenser and downstream ejector required.
2. Higher-than-design tubeside DP.	2. Poor condenser performance: a. tubeside fouling b. Higher-than-design cooling water flow.	2. a. Clean tubes b. Not a problem
3. Higher-than-design tubeside DT.	3. Poor condenser performance: a. Low cooling water flow b. Higher-than-design duty.	3. a. Increase flowrate b. Increase cooling water flowrate or replace condenser.
4. High vapor outlet temp.	4. Poor condenser performance.	4. a. Tube fouling b. Cooling water flowrate low or inlet temperature high c. Possible internal bypassing. Check with manufacturer d. Downstream ejector not functioning and back streaming.

This may occur a couple of different ways. If the condensing profile is such that condensible hydrocarbons are not condensed as they were designed to, then the amount vapor leaving the condenser increases. Ejectors may not tolerate this situation, resulting in unstable operation.

Another possible effect of increased condensible hydrocarbon loading is an increased oil film on the tubes. This reduces the heat-transfer coefficient. Again, this situation may result in increased vapor and gas discharge from the condenser. Unstable operation of the entire system may also result.

To remedy performance shortcomings, new condensers or ejectors may be necessary.

Table 3. System operating survey

	Measured at the plant	Original design
Tower overhead temperature, °F	158	150
First stage ejector suction pressure, mmHg Abs.	54	20
First stage ejector discharge pressure, mmHg Abs.	132	90
Second stage ejector suction pressure, mmHg Abs.	128	86
Third stage ejector suction pressure, mmHg Abs.	180	241
Cooling tower water temperature, °F	95	90
Temperature rise across first intercondenser, °F	15	18.5
Tubeside pressure drop across first intercondenser, psi	19	10
Temperature rise across second intercondenser, °F	2	2.5
Tubeside pressure drop across second intercondenser, psi	7	2.9
Temperature rise across the aftercondenser, °F	7	5
Motive steam pressure, psig	150	150
Backpressure on aftercondenser vent, psig	0	0

Tower overhead loading. In general, a vacuum system will track tower overhead loading as long as noncondensible loading does not increase above design. Tower top pressure follows the first-stage ejector's performance curve. Fig. 4 shows a typical performance curve. At light tower overhead loads, the vacuum system will pull tower top operating pressure down below design. This may adversely affect tower operating dynamics and pressure control may be necessary.

Tower pressure control is possible with multiple element trains. At reduced overhead loading, one or more parallel elements may be shut off. This reduces handling capacity, permitting tower pressure to rise to a satisfactory level. If multiple trains are not used, recycle control is another possible solution. Here, the discharge of an ejector is recycled to the system suction. This acts as an artificial load, driving the suction pressure up. With a multiple-stage ejector system, recycle control should be configured to recycle the load from before the first condenser back to system suction (Fig. 5). This way, noncondensible loading is not allowed to accumulate and negatively impact downstream ejectors.

System back pressure. Vacuum system back pressure may have an overwhelming influence on satisfactory performance. Ejectors are designed to compress to a design discharge pressure. If the actual discharge pressure rises above design, the ejector will not have enough energy to reach the higher pressure. When this occurs, the ejector breaks operation and there is a sharp increase in suction pressure.

When back pressure is above design, possible corrective actions are to lower the system back pressure, rebore the steam nozzle to permit the use of more motive steam or install a completely new ejector.

Operating survey. The most practical way to troubleshoot a vacuum system is to perform a pressure and temperature profile while the system is in normal operation. Then compare the readings with the origin design criteria. Before performing a survey, it is critical to have accurate instrumentation like calibrated thermometers, pressure gauges and an absolute pressure gauge for vacuum readings.

Readings that should be taken include:

- Motive steam pressure and temperature measured as close as possible to each ejector's inlet
- Suction and discharge pressure and temperature of each ejector
- Cooling water inlet and outlet temperature of each condenser
- Tubeside pressure drop across each condenser
- Condensate temperature from each condenser, if available.

With these readings, a step-by-step comparison against the original design criteria should allow a determination of the cause for a deficiency in the system.

Tables 1 and 2 will help in analyzing the system to determine any problems. Table 1 pertains to ejector performance and the areas that effect an ejector, namely, motive steam pressure and quality, suction load and discharge pressure. Table 2 relates to condenser performance.

If there are still questions as to the exact problem after completing the above evaluation, it is advisable to contact the original manufacturer or have a qualified vacuum service engineer visit the site to help analyze the system.

CASE HISTORY

Operating survey of a vacuum system on a crude tower in a South American refinery. Problem: The refiner was dissatisfied with the vacuum tower operating pressure. Tower top pressure exceeded its design value. Table 3 shows the results of the system operating survey that was conducted.

The system was shut down and equipment inspected. Dimensionally, the ejectors were in satisfactory condition, but the second-stage ejector showed signs of erosion. The second-stage ejector diffuser throat was 4% to 5% larger in diameter than design. Each ejector had a heavy hydrocarbon film on the motive steam nozzle exterior and air chamber.

The first intercondenser was heavily fouled on the tube and shellside. The tubeside had an excessive white scale that caused the high tubeside pressure drop. The shellside had a heavy black film coating the tubes. This was similar to what was noticed in the ejectors. The secondary condensers had similar fouling deposits.

Solutions: The higher-than-design cooling water temperature and excessive fouling of the condensers affected condenser performance to the extent that inadequate condensation was taking place. The impact of this was with the ejectors. Higher vapor loads exiting the first intercondenser could not be handled by the second-stage ejector at 86 mmHg Abs. This forced the first-stage ejector to break operation resulting in a substantial increase in tower operating pressure.

Quotes were made to replace existing condensers with new ones having higher design fouling factors and based on higher cooling water temperature. Once installed, tower top pressure was at design and operation was stable.

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