Understanding ejector systems necessary to troubleshoot vacuum distillation

James R. Lines Graham Corp. *Batavia, NY*

A complete understanding of ejector system performance characteristics can reduce the time and expense associated with troubleshooting poor crude vacuum distillation unit (CVDU) performance.

Variables that may negatively impact the ejector-system performance of vacuum-crude distillation units include utilities supply, corrosion and erosion, fouling, and process conditions.

Fig 1.

Fig. 2

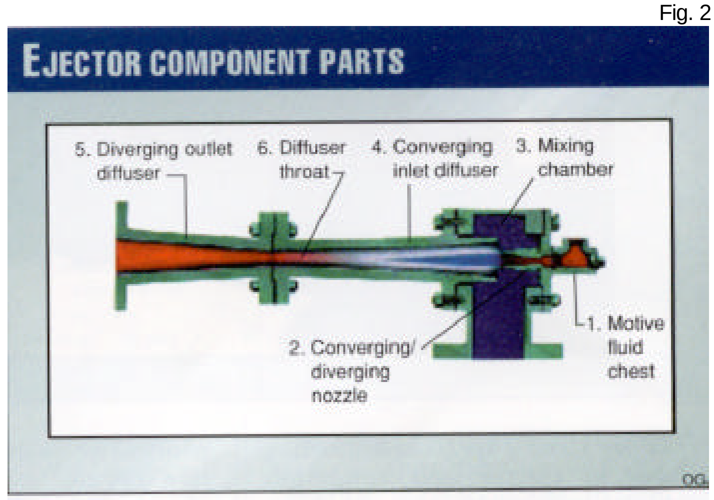
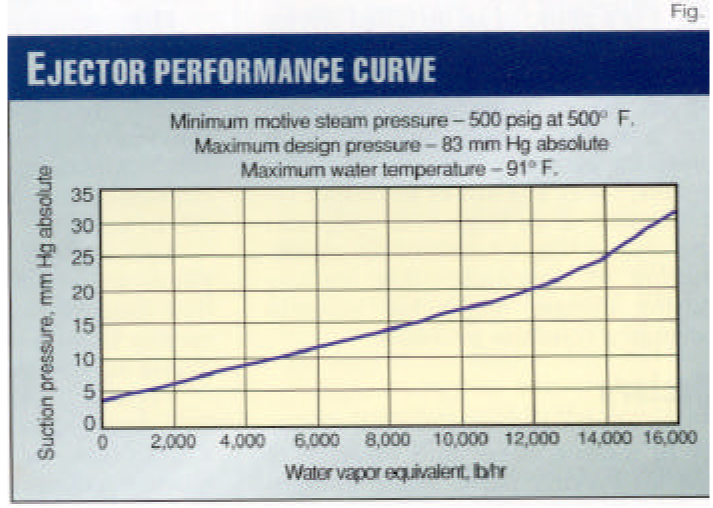


Fig.



WET-STEAM DAMAGE

Erosion of inlet diffuser Fig. 4a

Erosion of diffuser inlet and scale buildup on diffuser outlet Fig. 4b

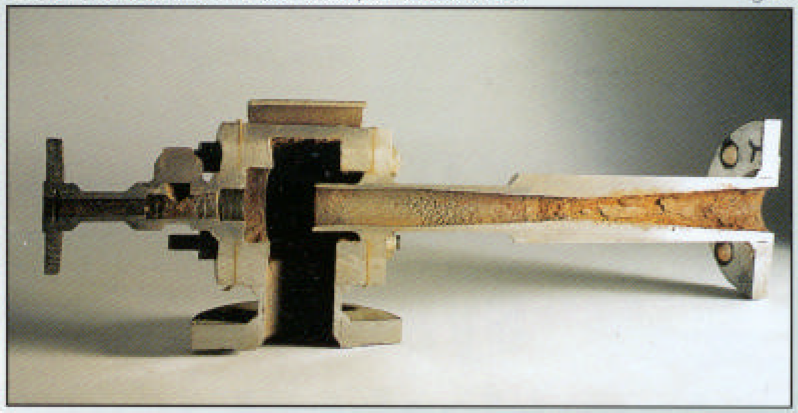


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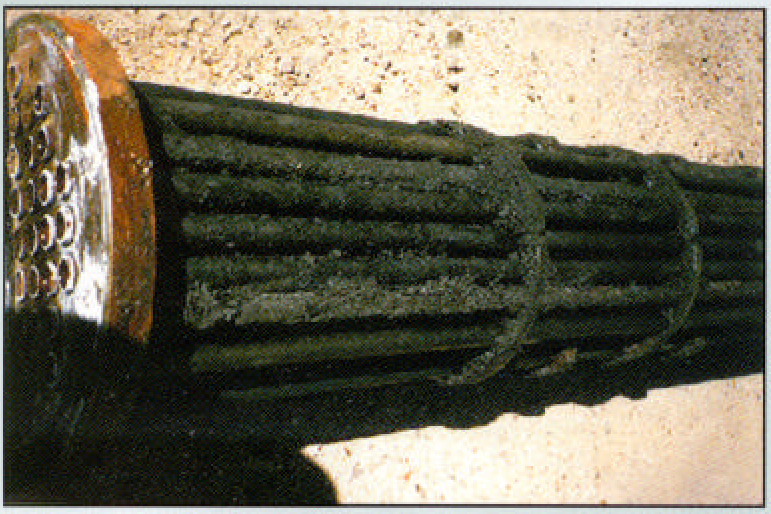
Fig. 5

INTERCONDENSER FOULING



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Tables 1 and 2 are troubleshooting guides to ejector and condenser problems in vacuum ejector systems. Fig. 1 is a photo of an installed ejector at a CVDU.

Two actual case studies conducted by service engineers on CVDU-ejector systems show how to troubleshoot ejector problems. The first problem was a result of improper replacement of an intercondenser, and the second was a result of underestimation of noncondensible loading during design, which has recently become a common problem.

Ejectors

An ejector converts pressure energy of motive steam into velocity. It has no moving parts. Major components of an ejector consist of the

motive nozzle, motive chest, suction chamber, and diffuser (Fig. 2).

High velocity is achieved through adiabatic expansion of motive steam across a convergent/divergent steam nozzle. This expansion of steam from the motive pressure to the suction fluid operating pressure results in supersonic velocities at the exit of the steam nozzle.

The motive steam actually expands to a pressure below the suction fluid pressure. This expansion creates a low-pressure region, which draws suction fluid into an ejector.

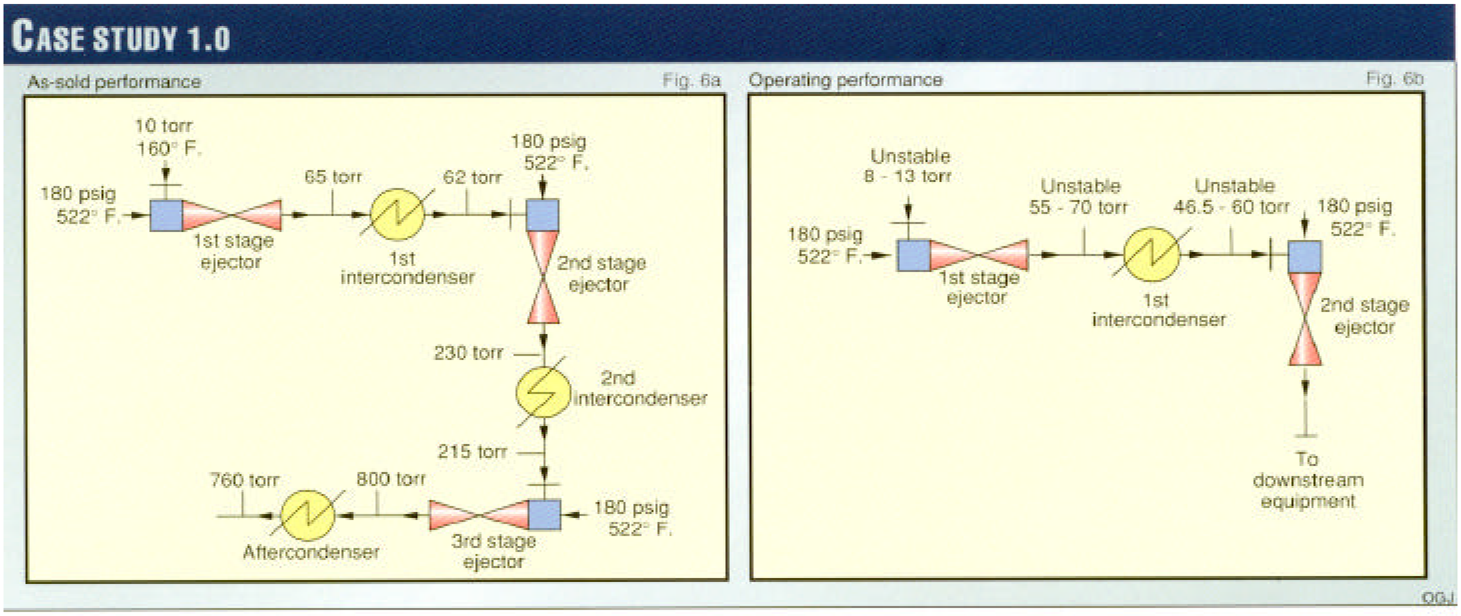
Typically, velocity exiting a motive steam nozzle is in the range of 3,000-4,000 fps. This high-velocity motive steam then entrains and mixes with the suction fluid. The resultant mixture is still supersonic. As the mixture passes through the **con**vergent, throat, and divergent sections of a diffuser, high velocity is converted back to pressure.

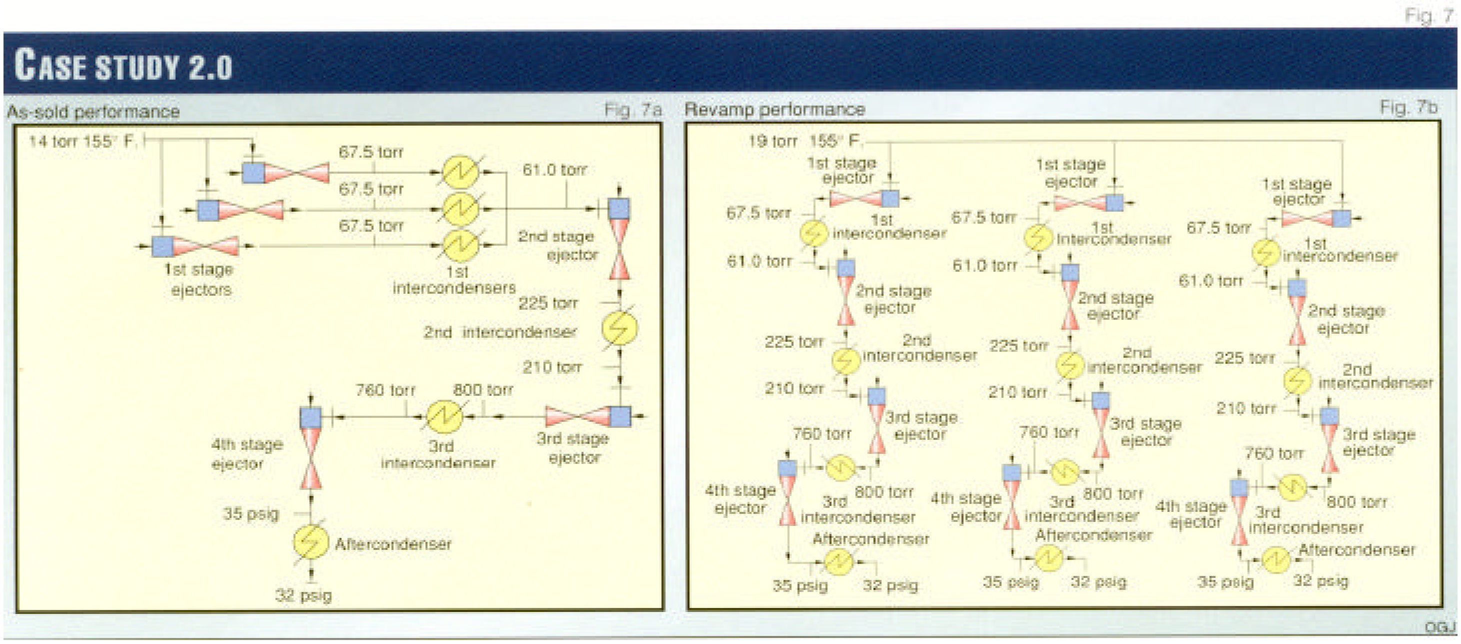
The convergent section of a diffuser reduces velocity as cross sectional area is reduced. Intuitively, one normally thinks that as flow area is reduced, velocity is increased. But a unique thermodynamic phenomenon occurs with gases at supersonic conditions: As cross-sectional flow area is reduced, the velocity is reduced.

The diffuser throat is designed to create a shock wave. The shock wave produces a dramatic increase in pressure as the flow goes from supersonic to subsonic across it. In the divergent section of the diffuser, cross-sectional flow area is increased and velocity is further reduced and converted to pressure. A shock wave occurs in the diffuser throat when the compression ratio of an ejector is 2:l or greater, which is the case with CVDU ejector systems.

An ejector-performance curve gives the expected suction pressure as a function of water-vapor equivalent loading (Fig. 3). Heat Exchange Institute Standards for Steam Jet Ejectors describes the method to convert the mixture (air, water vapor, and various hydrocarbons) to a water-vapor equivalent or an air-equivalent load.

Other important information noted on an ejector performance curve includes the minimum motive steam pressure, the maximum motive steam temperature, and





the maximum discharge pressure.

If field measurements differ from a performance curve, then there may be a problem with the process, utility supply, or the ejector itself.

Condensers

A condenser in an ejector system reduces the amount of vapor load that a downstream ejector must handle. Condensers of an ejector system are designed to condense steam and condensible hydrocarbons and cool noncondensible gases.

In many cases, the inlet load to a condenser is many times greater than the load to a downstream ejector. Consequently, any loss in condenser performance will have a dramatic ef-fect on a downstream ejector.

Although vacuum condensers are constructed like process shell-and-tube heat exchangers, their internal designs differ significantly due to the presence of two-phase flow, noncon-densible gas, and vacuum operation.

Vacuum condensers for crude-tower applications have cooling water on the tube side. Condensation of water vapor and hydrocarbons takes place on the shellside. A major portion of the condensibles contained in the inlet stream (shell side) change from a vapor to liquid phase. The remaining condensibles and the noncondensible gases are removed from the condenser through a vapor-outlet connection by a downstream ejector.

Intercondensers are positioned be-tween two ejector stages. Condensation of intercondensers occurs at a pressure corresponding to the dis-charge pressure of a preceding ejector and the suction pressure of a downstream ejector.

Steam pressure and temperature

The temperature and pressure of motive-steam supply is one of the most important variables affecting ejector operation. If the pressure falls below design pressure, then the motive nozzle will pass less steam. If this occurs, an ejector does not have enough energy to entrain and compress a suction load to the design discharge pressure.

Similarly, if the motive-steam supply

Table 1

EJECTOR TROUBLESHOOTING

	Problem	Effect	Corrective action
1	Lower than design motive-steam pressure.	Poor ejector performance.	Raise steam pressure or bore steam nozzles.
2	Higher than design motive-steam pressure.	Reduced ejector capacity and wasted steam.	Reduce motive pressure or replace steam nozzles with new nozzles designed for a higher steam pressure.
3	Higher than design steam temperature (50° F.+).	Poor ejector performance.	Raise steam pressure or bore steam nozzles.
4	Higher than design discharge pressure.	Poor ejector performance.	Look downstream for problems: 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.	Reduced ejector capacity or poor performance.	a. Insulate steam lines b. Add moisture separator in 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).	Greater than design load or mechanical problems with ejector. Either worn out internals or possible internal steam leak around steam-nozzle threads.	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 TROUBLESHOOTING

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

temperature is appreciably above the design value, insufficient steam passes through the motive nozzle. Both lower-than-design steam pressure and higher-than-design steam temperature increase the specific volume of the motive steam and reduces the amount of steam through a motive nozzle.

In certain cases, it is possible to re-bore an ejector-motive nozzle to permit the passage of more steam through the nozzle, thereby increasing the energy available to entrain and compress the suction load.

If motive-steam pressure is more than 20% above design, too much steam expands across the nozzle. This often chokes the diffuser throat of an ejector. When this occurs, less suction load is handled by an ejector, and the CVD-column pressure rises. If an increase in column pressure is undesirable, then new ejector nozzles with smaller throat diameters are required.

Table 3

VACUUM-TOWER OVERHEAD COMPOSITION

	Design		Actual	
	Flow rate, lb/hr	Molecular wt	Flow rate, lb/hr	Molecular wt
Noncondensible gas	700	40	1,500	32
Water vapor	13,000	18	15,000	18
Condensible hydrocarbon	7,500	170	13,000	170

Steam quality

Wet steam is very damaging to an ejector system because high-velocity moisture droplets are erosive. These droplets are rapidly accelerated as steam expands across a motive nozzle.

Erosion of nozzle internals caused by wet motive-steam is noticeable when inspecting ejector nozzles or diffuser internals. There is an etched striated pattern on the diverging section of a motive nozzle, and the nozzle mouth may actually wear out. Also, the inlet diffuser section of an ejector will show signs of erosion as a result of direct impingement of moisture droplets (Fig. 4a).

Fig. 4b depicts an ejector cutaway showing severe damage caused by wet steam. The inlet diffuser shows substantial metal loss. Metal-scale buildup can be seen in the outlet diffuser section.

The exhaust temperature from the ejector can determine if the steam conditions are present. Typical ejector exhaust temperatures are in the range of 250 to 300° F. If moisture is present, a substantially lower exhaust temperature will exist.

To solve wet-steam problems, all lines up to an ejector should be well insulated. A steam separator and trap should be installed immediately before the motive-steam inlet connection of each ejector. In some instances, a steam superheater may be required.

Wet steam can also cause performance problems. Moisture droplets through an ejector nozzle decrease the energy available for compression. This reduces the suction-load handling capacity of an ejector.

Also, the moisture droplets may vaporize within the diffuser section of the ejector. Upon vaporization, the volumetric flow rate within the ejector increases. Here again, this reduces the suction-load capacity of an ejector.

Cooling water conditions

A rise in cooling-water temperature lowers the available log mean temperature difference (LMTD) of a condenser. Should this occur, the condenser will not condense enough steam and condensible hydrocarbons. This will increase the vapor load to the downstream ejector.

As a result of inadequate condensation, there also is an increase in pressure drop across the condenser. If an ejector following this condenser cannot handle an increased vapor load at the operating pressure of a condenser, the operating pressure of the condenser will rise and the system will break performance.

Broken ejector system performance is characterized by a higher-than-design CVDU tower-top pressure. The tower-top pressure may become unstable.

This may also occur if the cooling-water flow rate is below design. At lower-than-design flow rates, there is a greater water-temperature rise across a condenser. Here again, this will lower the available LMTD. Poor performance is further exacerbated as a result of a lower heat transfer coefficient resulting from low-water flow rate.

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

THE AUTHOR

Lines

James R. Lines is vice-president, marketing, for Graham Corp. He has held positions as an application engineer, product supervisor, sales engineer, and vice-president, engineering.

Lines holds a BS degree in aerospace engineering from the University of Buffalo.

Corrosion and erosion

Corrosion may occur in ejectors, condensers, or Vacuum piping. Extreme corrosion may cause holes and allow a system. Air leakage into the vacuum system. Air leakage into a vacuum system will deteriorate performance and can result in broken ejector operation.

A common corrosion problem occurs when carbon-steel tubing is used in condensers. Although carbon steel may be suitable for the crude feed-stock, it is not always the best choice for an ejector system. Although carbon steel has a lower capital cost, operating problems can outweigh modest up-front savings.

During extended periods of shutdowns for maintenance or revamps, a condenser with carbon-steel tubing will be exposed to air, oxidize, and develop a scale buildup. When an ejector system starts up, this buildup can severely foul the condensers and prevent proper operation of the vacuum system.

Poor steam quality and high velocities may also cause erosion of the diffuser and motive-nozzle internals. Ejector manufacturers will provide certified information that defines the motive nozzle and diffuser throat 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 are necessary.

Threaded steam connections may experience a phenomenon termed wire drawing, or wire cutting. Loose threads provide a leak path for the steam. Over time, the steam will destroy the threaded joint or even put a hole in the piece. A hole leads to a steam leak within the ejector, which will act like a suction load, thereby reducing the system's performance.

Fouling

Intercondensers and aftercondensers are subject to fouling on both the tube side and the shell side. Fouling deters heat transfer.

Cooling-tower water, often used as the cooling fluid for vacuum condensers, is normally on the tube side. Over a prolonged period of time, actual fouling may exceed the design value, and condenser performance becomes inadequate.

Vacuum-tower overhead gases, vapors, and motive steam are normally on the shell side of a condenser. Depending on fractionation and the type of crude processed, a hydrocarbon film may develop on the outside surface of the tubing. This film deters heat transfer.

Fig. 5 illustrates how severely a condenser may be fouled. In this example, not only did the tubing have a hydrocarbon film, but solidified hydrocarbon product adhered to the tubing. The solidified material blocked the flow, resulting in poor performance and an elevated pressure drop.

When actual unit fouling exceeds design values, a condenser performs inadequately. Once fouled, a condenser is unable to condense sufficient quantities of hydrocarbon vapors and motive steam. The result of condenser fouling is an increase in vapor load to a downstream ejector and an increase in condenser-operating pressure. Ultimately, a preceding ejector will break operation.

Routine refinery procedures should include periodic cleaning of the tube side and the shell side of condenser bundles.

Process conditions

Vacuum system performance may be affected by several process variables: non-condensible gas loading, condensible hydrocarbons, and vacuum system back pressure.

Ejector systems are susceptible to poor performance when noncondensible loading increases above design. Noncondensible loading to an ejector system can be caused by air leakage into the system, the presence of light hydrocarbons, or the existence of cracked gases from a fired heater.

The impact of higher-than-design noncondensible loading is severe. As noncondensible loading increases, the amount of saturated vapors discharging from a condenser increases proportionately.

The ejector following a condenser may not be able to handle increased loading at that operating pressure of the condenser. The ejector preceding that condenser is unable to compress to a higher discharge pressure. This discontinuity in pressure causes the preceding ejector to break operation.

When actual noncondensible loading is consistently above design, new ejectors are required. Depending on the severity of noncondensible overloading, new condensers may be required as well. Recently, several CVDU revamps in the U.S. Gulf Coast experienced startup difficulties due to inaccurate estimates of actual noncondensible loading.

As different crude oils are processed, or as refinery operations change, the composition and amount of condensible hydrocarbons handled by an ejector system vary. Condensable hydrocarbon loading may become so much greater than design that condenser or ejector performance is adversely affected.

Another possible affect of increased condensible hydrocarbon loading is an increased oil-condensate film on the tubing, and consequently, a reduction in the heat transfer rate. This situation may result in increased vapor discharge from a condenser. Unstable operation of the entire ejector system may result. To overcome this type of performance limitation, new condensers or ejectors may be required.

Vacuum system back pressure may have an overwhelming influence on satisfactory performance. If the actual discharge pressure rises above design, an ejector will not have enough energy to reach that higher pressure. When this occurs, the ejector breaks operation, and there is an increase in CVDU tower-top pressure.

When back pressure is above design, possible corrective actions include lowering the system back pressure, reboring the steam nozzle to permit the use of more motive steam, or installing new ejectors.

Case 1: Improper intercondenser

A West Coast refiner experienced erratic system performance after replacing an intercondenser supplied by the ejector system manufacturer with one designed and built by a local heat exchanger fabrication shop. The ejector system vendor dispatched a service engineer to investigate the cause of the problem without knowing about the replacement intercondenser.

The actual performance of the system differed from the "as sold" system (Fig. 6). The first-stage ejector was operating in a broken mode with both suction and discharge pressure remaining unstable. Pressure drop across the first intercondenser was excessive -at 8.5 mm Hg instead of 3 mm Hg.

Broken first-stage ejector performance and high-pressure drop across the first intercondenser suggested one of the following problems: fouling, cooling-water flow rate limitation, high inlet water temperature, or excessive hydrocarbon loading.

Prior to detailing a method to determine the actual cause, the service engineer discussed general performance characteristics with unit operators. At that time, he discovered that the first intercondenser had been replaced by another vendor.

The vendor had matched the original unit's tube count and external dimensions, but failed to properly design the shellside side baffling to effectively manage hydraulic and thermal requirements.

Vacuum condensers have special shellside baffling to ensure minimal pressure drop, noncondensible gas cooling, and separation of noncondensibles and condensate. It is typical to have different baffle spacing at strategic locations within the shell.

The vendor of the replacement condenser used conventional software to model the performance. The new condenser design had a fully baffled flow, and consequently a high-pressure drop.

In this instance, the high-pressure drop across the intercondenser caused the system to break performance. The first-stage ejector could not overcome the added pressure drop and reach a discharge pressure in which the second-stage ejector would operate.

Once the replacement unit was pulled out and a properly designed condenser put in, system performance was satisfactory.

Case 2: Underestimated loading

A U.S. Gulf Coast refiner grossly underestimated its noncondensible loading when it modernized a CVDU to process sour South American crude. The modernization effort involved an entirely new ejector system.

Upon startup of the CVDU, the ejector system was not performing properly. Tower-top pressure was significantly above design, and it was unstable.

Initial investigation verified utility conditions. The ejector system was designed for 140 psig motive steam, and the actual supply pressure varied between 138 and 144 psig.

Next, the cooling water was evaluated. Design inlet temperature was 88° F., and the actual supply temperature was at 72.3° F. Temperature rise and pressure drop across each condenser did not suggest an abnormality. The equipment was new, so fouling was ruled out.

A detailed analysis of the sour South American crude oil was in order.

The design and actual vacuum tower overhead compositions are shown in Table 3.

The actual simulation was too different from design conditions. Significant equipment modifications were needed to achieve the desired charge rate and vacuum level.

The steam equivalent loads were calculated to be about 17,500 lb/hr and 23,000 lb/hr for design and actual loading, respectively. According to the performance curve, at the higher load, the first-stage ejector would maintain about 19 mm Hg absolute pressure in lieu of the design 14 mm Hg. The refiner agreed to accept the higher pressure.

Because the noncondensible loading values were drastically different (more than twice as much as design) new equipment was necessary.

The refiner added redundant ejectors and condensers after the first intercondensers to handle the additional noncondensible load. The system stabilized after two parallel trains of secondary equipment were installed. Tower-top pressure was still above design but within an acceptable range.

Figs. 7a and 7b depict the "as sold" performance and the revamped operation.