A simple ejector modification

A vacuum column's economics can be greatly improved with a low cost modification to the ejector system

JIM LINES
Graham Corporation

Refiners can benefit from improved yield and lower vacuum residuum, thus improving refinery economics with minor modifications to the ejector system. Refiners continually optimise their crude slate, push the vacuum column for greater throughput and, for a variety of other reasons, operate the vacuum distillation unit under conditions differing from the design basis. This can lead to dramatic increases in vacuum column pressure, especially during summer months when cooling water is warmest. Refiners have benefitted from modification to the first stage ejector motive steam nozzle (see **Figure 1**) to overcome losing millions of dollars during summer months when column pressure abruptly rises, yield declines and vacuum residuum increases. In the parlance of ejector systems, during the summer months ejector performance breaks, shockwave is lost and vacuum column pressure increases dramatically.

Ejector systems

Ejector systems are a combination of ejectors and condensers that evacuate and maintain sub-atmospheric pressure in a vacuum distillation column. Column overhead vapours consisting of non-condensable gases, hydrocarbon vapours, and steam are evacuated continually from the column and compressed above local barometric pressure, typically to 2-5 psig.

It is helpful to understand the operating principle of an ejector where the compression ratio is nominally two or greater and discharge pressure is greater than two times the suction pressure. Ejectors are static equipment with no moving parts. The operating principle follows compressible flow theory. Medium or low pressure steam, typically less than 250 psig, is the energy source that performs the work and creates the vacuum. Steam is expanded isentropically across a converging-diverging nozzle where its pressure is reduced and converted to supersonic velocity. This pressure reduction and expansion to supersonic flow is what creates the vacuum. The low pressure region exiting the converging-diverging nozzle is lower than the distillation column pressure, thereby inducing flow from the column and pulling the non-condensable gases plus saturated vapours, both steam and hydrocarbons, into the ejector. The vacuum column discharge is referred to as suction load or overhead loading to the first stage ejector. The suction load is entrained by and mixes with the high velocity motive steam, and the combined flow remains supersonic.

Again, compressible flow theory is applied where the supersonic mixture of overhead load and motive steam passes through another converging-diverging conduit, referred to as a diffuser, where high velocity is converted back to pressure. A fundamental principle for compressible flow, which may be counter-intuitive, is that when flow is supersonic and the cross-sectional area of a flow path

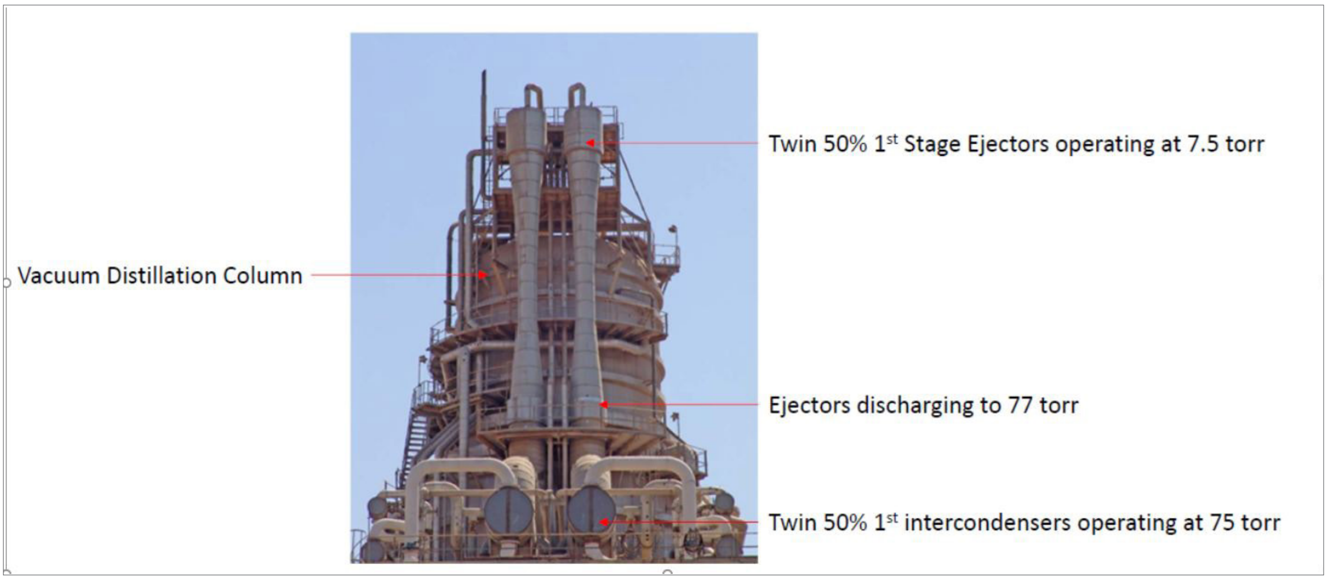

Figure 1 Crude distillation vacuum column twin element ejector system

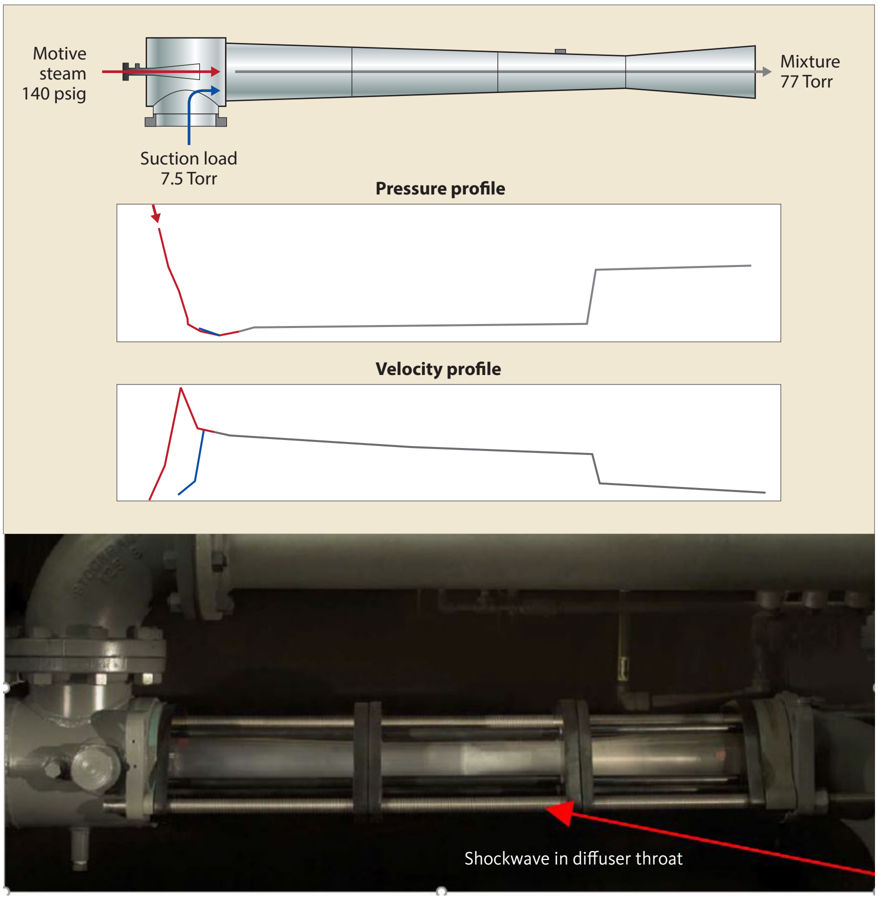

Figure 2 Ejector pressure profile and shockwave

is progressively reduced, velocity actually decreases. The throat of the converging-diverging diffuser section of the ejector is where cross-sectional area is the smallest and a shockwave is established, which serves to boost pressure. **Figure 2** illustrates pressure and velocity profiles across an ejector with a clear step up in pressure at the throat where a shockwave is established.

An ejector, unlike a piston reducing volume to increase pressure, does not create a discharge pressure. Motive steam provides the energy necessary to compress and flow the mixture of motive and overhead load to the operating pressure of a downstream condenser. If the pressure of the condenser is below the discharge capability of the ejector, the ejector will not cause the condenser to operate at a higher pressure. Conversely, if the operating pressure of a condenser downstream of an ejector is above the discharge capability of that ejector, referred to as a maximum discharge pressure (MDP), the performance of the ejector breaks down, the shockwave is lost, and typically suction pressure moves sharply higher. This breakdown happens because there is insufficient energy provided by the motive steam to compress to a pressure above the MDP of the ejector. Suction pressure and therefore distillation column pressure may surge or become unstable once the shockwave is no longer present.

This broken ejector operation is what can be remedied inexpensively and will provide enormous payback when ejector break is caused by:

- Cooling water temperature above design
- Excessive condensable hydrocarbon loading
- Fouling above the design basis

These three are rather common causes for performance shortfall by the vacuum distillation ejector systems.

Consider **Figure 1** where the design basis for the vacuum column overhead and first stage ejector suction pressure is 7.5 torr and the first intercondenser when supplied with 85°F cooling water will operate at 75 torr. It is common in June-August to have refiners frustrated because the column overhead pressure is not 7.5 torr in this case, but much higher such as 20-25 torr. This results in tremendous lost profit due to substantial reduction in yield with commensurate increase in vacuum column bottoms or residuum.

During the hottest days of summer a refiner's cooling tower may be strained, and supply temperature to the first intercondenser exceeds 85°F. This can cause the first stage to break performance. As cooling water temperature rises above the 85°F design basis, the first intercondenser pressure rises. When it rises above the discharge capability of the first stage ejector, performance breaks, the shockwave is lost, and vacuum column pressure rises dramatically.

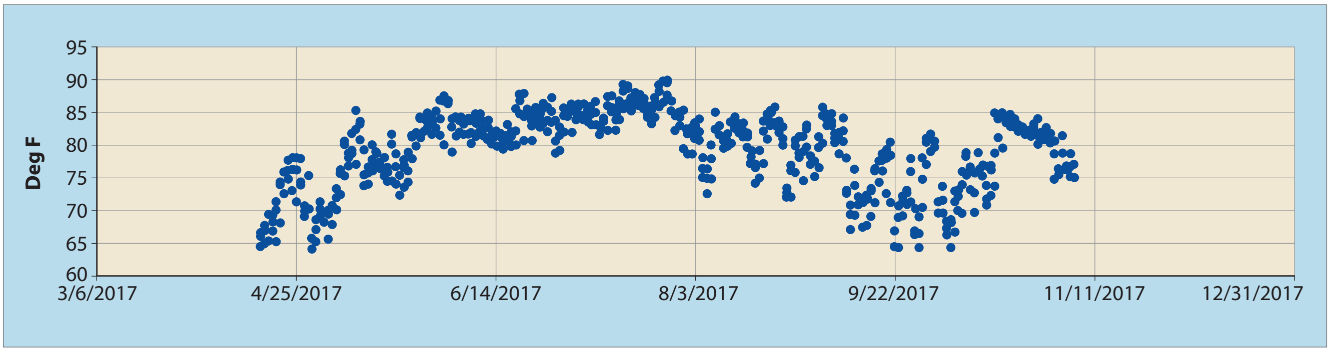

Figure 3 Cooling water inlet temperature to first intercondensers

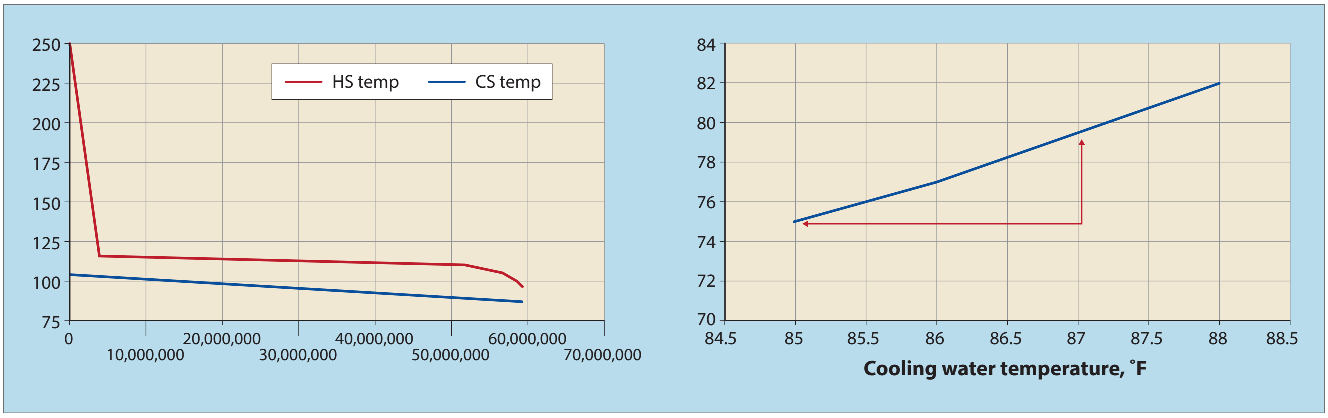

Figure 4 **Left:** If the inlet cooling water temperature rises above 85°F, assuming no other changes, the condenser rises to increase the temperature at which condensation occurs, thus increasing the LMTD **Right:** If the cooling water inlet temperature rises from 85°F to 87°F then first condenser pressure will rise from 75 torr to 79.5 torr. This exceeds the MDP of the first stage ejector and performance breaks down. A 7.5 torr vacuum column pressure jumps to c$_{2}$o torr, thereby substantially increasing residuum or lowering yield

This particular refiner provided output from the data historian for actual cooling water supply temperature. It was evident that summer months would present a performance risk for the ejector system as more than 27 days had periods where the water temperature was above the design basis of 85°F (see **Figure 3**).

The impact of a warmer cooling water inlet temperature is that condenser pressure must rise. The heat load at the ejector exhaust will be condensed when an intercondenser is present. The critical variable becomes at what pressure must the condenser operate to condense the ejector exhaust. The standard thermal duty equation follows:

Thermal Duty = Area * Heat Transfer Rate * LMTD

where:

- Thermal duty is the condensation and cooling load from the ejector exhaust in Btu/hr, and this is fixed or unchanged for all intent and purposes
- Area is the heat exchange area of the intercondenser in ft^2, which is fixed for the installed exchanger
- Heat transfer rate is the overall heat transfer rate in Btu/hr ft^2 °F, which is essentially constant provided overhead load composition is unchanged
- LMTD is the logarithmic temperature difference between the hot side and cold side fluids in °F

If duty, area and transfer rate are fixed, the only variable to affect is LMTD. As cooling water temperature rises above the design basis of 85oF, condenser pressure rises which increases the initial dewpoint and condensing profile such that LMTD is increased, permitting the load to be rejected.

Figure 4 illustrates how condenser pressure is impacted by cooling water temperature. When the cooling water inlet is 87°F, to condense the ejector exhaust pressure in the intercondenser must rise to 79.5 torr to elevate the LMTD to compensate for warmer water temperature. That is 4.5 torr above the design basis, resulting in breakdown in the first stage ejector shockwave thus substantially increasing vacuum column pressure. The first stage ejector has a maximum discharge capability of 77 torr and cannot compress to 79.5 torr, thus breaking ejector performance.

A simple way to think about the thermodynamic aspects of the interplay between water temperature and intercondenser pressure is for this particular example, at 75 torr operating pressure with 85°F cooling water the initial steam dewpoint or condensing temperature is 113.8°F. When the water temperature is 87°F not 85°F, to adjust upward the LMTD to compensate for the hotter water temperature, the pressure rises to 79.5 torr where the initial steam dewpoint increased to 115.8°F, 2 degrees warmer.

Similarly, hydrocarbon loading in the vacuum column overhead can be considerably above the design basis. This happens due to changes in feedstock, operating overhead temperature warmer to avoid precipitating corrosive products or to improve throughput or yield overhead droplet or mist elimination is removed. When hydrocarbon loading increases appreciably above the design basis it lowers the overall heat transfer rate for the first intercondenser (the condenser to which first stage ejectors discharge). Referring back to the thermal duty equation, the variable that adjusts is LMTD. It must increase to overcome a reduction in overall heat

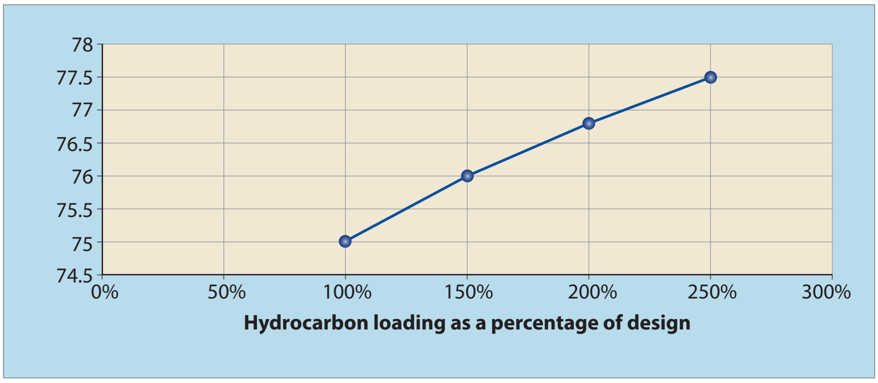

Figure 5 Hydrocarbon loading effect on condenser pressure

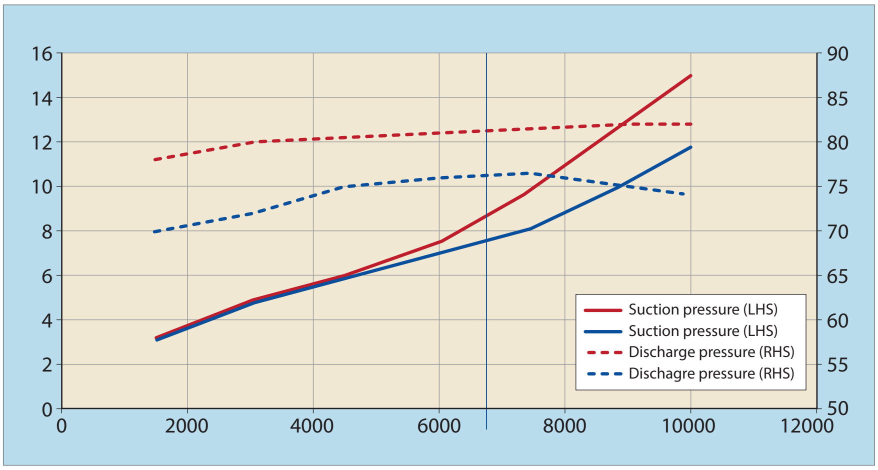

Figure 6 First stage ejector performance with original and new motive geometry

transfer rate due to excessive hydrocarbon loading in the overhead stream. Once again, intercondenser pressure rises to effectively increase LMTD such that the intercondenser can reject the ejector exhaust duty. **Figure 5** illustrates how intercondenser pressure rises to increase LMTD when hydrocarbon loading exceeds design. This illustration is indicative for this particular refiner's operating conditions.

When intercondenser pressure rises in response to excessive hydrocarbon loading, a pressure can be reached where first stage ejector discharge capability is exceeded, shockwave breaks down, and vacuum column pressure rises dramatically.

The same tendency occurs when fouling becomes excessive, causing pressure in the intercondenser to rise, thereby increasing LMTD to compensate for the resultant lowering in overall heat transfer rate.

A low cost fix

Reconfiguring the first stage ejector motive steam nozzle can be a low cost solution that pays back tremendously. It is possible to replace the existing motive steam nozzle with a new, different geometry tailored to achieve greater discharge capability without using anymore motive steam. For the same energy input or mass flow rate of motive steam, higher discharge pressure can be achieved by accepting minimally higher vacuum column overhead pressure. The trade-off is some modest increase in vacuum column pressure, however the installed ejector will have greater maximum discharge pressure capability.

Each case must be analysed and performance testing undertaken to optimise the new nozzle geometry for the installed diffuser configuration. The general rule is that if the motive nozzle is pushed in toward the diffuser throat then discharge capability will increase while suction capacity decreases slightly. The ejector nozzle mouth can be increased to extract more energy from the motive steam in the form of greater velocity to increase somewhat the suction capacity.

Recent projects where new, different motive nozzles were installed increased first stage ejector discharge pressure to overcome the effects of warmer cooling water, excessive hydrocarbon loading or a combination of both. In the case of excessive hydrocarbon loading, the refiner added mist elimination devices as well. Feedback has been positive and lost revenue remedied with a customised, low cost fix.

Figure 6 shows the first stage ejector performance curves for the system noted in **Figure 1**. Performance curves are provided for the original installation and after a tailored new nozzle geometry was installed to compensate for elevated intercondenser operating pressure caused by cooling water temperature or hydrocarbon loading above design conditions or a combination of both.

When the summer months arrived and the original ejector system broke operation and vacuum column overhead pressure rose to 18-24 torr, resulting in millions of dollars in lost profit. By tailoring new motive nozzles, the refiner accepted a 1.5 torr loss in suction pressure at design loading, 9 torr in lieu of 7.5 torr, while having 5 torr greater discharge capability to run well through the summer months without a break in performance (see **Figure 7**).

This type of low cost fix can have a large economic benefit. Don't let summer time vacuum column performance frustrate and result in economic losses when it is possible to remedy the issue in a low cost manner.

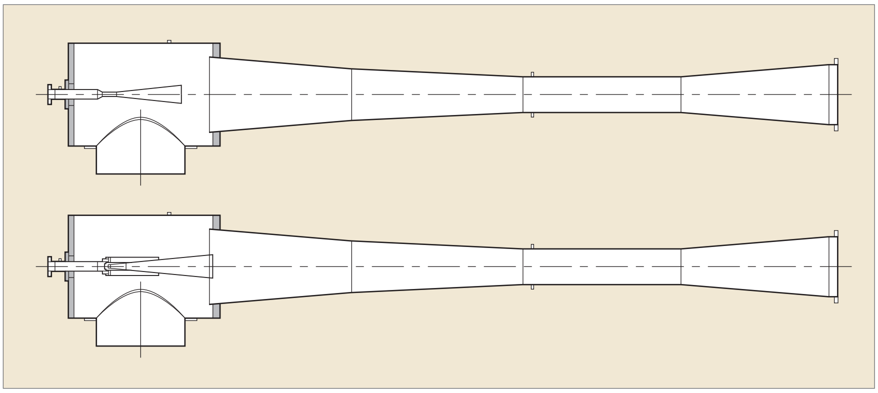

Figure 7 Original ejector and nozzle geometry and new nozzle geometry