For decades there has been a marked uncertainty regarding the operation of steam jet ejectors in downstream facilities. **Jim Lines, Graham Corporation, USA,** reviews the functionality, performance and considerations of this important technology.

A MYSTERY SOLVED

Crude oil refining, petrochemical and inorganic chemical industries use steam jet ejectors extensively for distillation, concentration and crystallisation processes. This has held true for many decades. There is, however, uncertainty or a lack of deep understanding about how an ejector functions, what affects their performance and important considerations for reliable, trouble-free operation. It is not uncommon for process engineers, maintenance and reliability engineers or static equipment engineers to consider ejectors a 'black box' shrouded in mystery about why they perform as they do. This article addresses important performance characteristics, the thermodynamics behind how an ejector performs, flow visualisation to look inside the black box, and a deeper overview for users of steam jet ejectors.

Steam jet ejectors

A steam jet ejector is a compressor that uses high pressure steam as the working fluid to boost the pressure of process vapours or gases. A principle service that ejectors perform is to reduce the pressure of a process and maintain this reduced pressure by continually extracting gases and vapours that are formed by the process. The image of an ejector system in crude vacuum distillation service, shown in Figure 1, identifies twin first stage ejectors attached directly to a vacuum column, so that the ejectors reduce the pressure within the column and continually extract vapours and cracked gases formed as crude oil is distilled. An ejector is a static component, generally made from material that is cast or that can be cold worked and welded. Figure 1 provides the nomenclature for standard parts of an ejector.

Steam jet ejectors fall into two classifications:

- Non-critical: where the discharge pressure is less than approximately 1.8 times the suction pressure.
- Critical: where the discharge pressure is more than approximately 1.8 times the suction pressure.

'Critical' is a term that refers to the presence of a shockwave in the diffuser throat that serves to boost the pressure, increasing the discharge pressure above that of the suction pressure. It is choked flow in the diffuser, correlated to

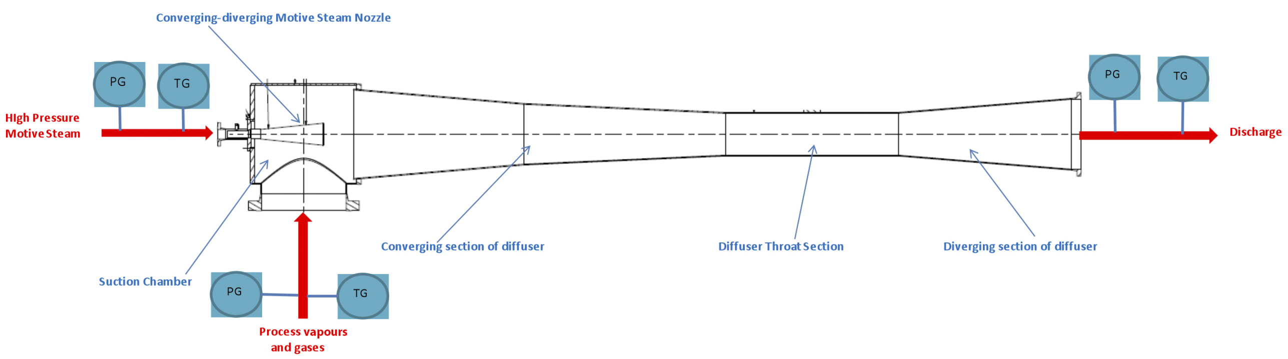


Figure 1. Steam jet ejector.

Table 1. Pressure and velocity relationship to area

Flow regime	Decreasing cross-sectional area	Increasing cross-sectional area
Subsonic, velocity ‹ Mach 1.0	Velocity increases Pressure decreases	Velocity decreases Pressure increases
Supersonic, velocity › Mach 1.0	Velocity decreases Pressure increases	Velocity increases Pressure decreases

Table 2. Critical pressure ratio and sonic velocity

Gas	MW	γ	Critical pressure ratio	Sonic velocity at 100°F
	lb/lb-mole	Dimensionless	Dimensionless	ft/sec.
Air	29	1.4	1.89	1160
Steam	18	1.33	1.85	1435
Helium	4	1.66	2.05	3400
Hexane	86	1.06	1.69	586
Phenol	94	1.09	1.70	568
N-Octane	114	1.05	1.68	507

sonic velocity, such that the mass flow rate passing through the motive nozzle or diffuser throat is at the speed of sound. This article covers the most common type of ejector that uses high pressure steam as the motive fluid and where the ratio of discharge to suction pressure exceeds the critical pressure ratio, above which flow is choked and a shockwave is present.

A brief overview of compressible flow theory is important. However, the complicated fluid flow and thermodynamics process can be best presented in simple terms.

Unique characteristics of compressible flow are shown in Table 1. Mach number is velocity relative to sonic velocity (speed of sound). Mach = 1 when velocity is equal to sonic velocity. Moreover, there is a critical pressure ratio above which flow is 'choked' and will not pass through a given cross-sectional flow area any faster than sonic velocity. This critical pressure ratio varies based on the type of gas and its properties. The generalised formula for critical pressure ratio is shown in Equation 1:

$$\frac{P\,motive}{P\,suction}=\left(\frac{\gamma+1}{2}\right)^{\gamma/\gamma-1} \text{ or } \frac{P\,discharge}{P\,suction}=\left(\frac{\gamma+1}{2}\right)^{\gamma/\gamma-1}$$

Where *P motive* = pressure of motive steam; *P suction* = suction pressure to ejector; *P discharge* = ejector discharge pressure; and γ = ratio of fluid specific heats. Different fluids will have different sonic velocities and critical pressure ratios, as Table 2 notes. Higher molecular weight gases will have a lower sonic velocity and, alternatively, higher temperatures result in greater sonic velocity.

An ejector leverages the behaviour of compressible fluids to first develop supersonic velocity by expanding high pressure motive across a converging-diverging nozzle down to a pressure that is below the suction pressure of the ejector. The ratio of the motive pressure to suction pressure is always many times greater than the critical pressure ratio, resulting in sonic velocity at the throat of the converging-diverging nozzle and supersonic flow in the diverging section of the nozzle. When the ratio of motive steam pressure to suction pressure is greater than the critical pressure ratio, flow through the throat of the converging-diverging nozzle is sonic and the corresponding mass flow rate that will pass through the nozzle is approximated by Equation 2.

When pressure and density are known:

$$Mass\ flowrate = 1336 * C_d * Throat^2 * (\gamma * P * \rho)^{1/2} * \left(\frac{2}{\gamma+1}\right)^{\left(\frac{1}{\gamma-1}+1/2\right)}$$

When pressure and temperature are known:

$$Mass\ flowrate = 409 * C_d * P * Throat^2 * \left(\frac{MW\gamma}{T}\right)^{1/2} * \left(\frac{2}{\gamma+1}\right)^{\left(\frac{\gamma}{\gamma-1}-1/2\right)}$$

Where *mass flow rate* = lb/hr; C_d = nozzle discharge coefficient (dimensionless); *Throat* = nozzle throat dia. (in.); γ = ratio of specific heats (dimensionless); *P* = motive pressure, PSIA (lb/in^2 absolute); *T* = motive temperature (degrees Rankine); *MW* = molecular weight (Lbf/lbm-mole); and ρ = motive density (lb/ft^3).

By expanding to a pressure lower than the suction pressure, this will induce a flow of process vapours into the ejector where it mixes with, and is entrained by, the high velocity motive steam. This mixture velocity is still supersonic. Figure 2 depicts isentropic expansion and the development of supersonic flow.

Flow across a motive steam converging-diverging nozzle, assuming no heat addition or removal and inviscid flow, follows a one dimensional energy equation, and total (stagnation) enthalpy is constant throughout the nozzle. The velocity ahead of the

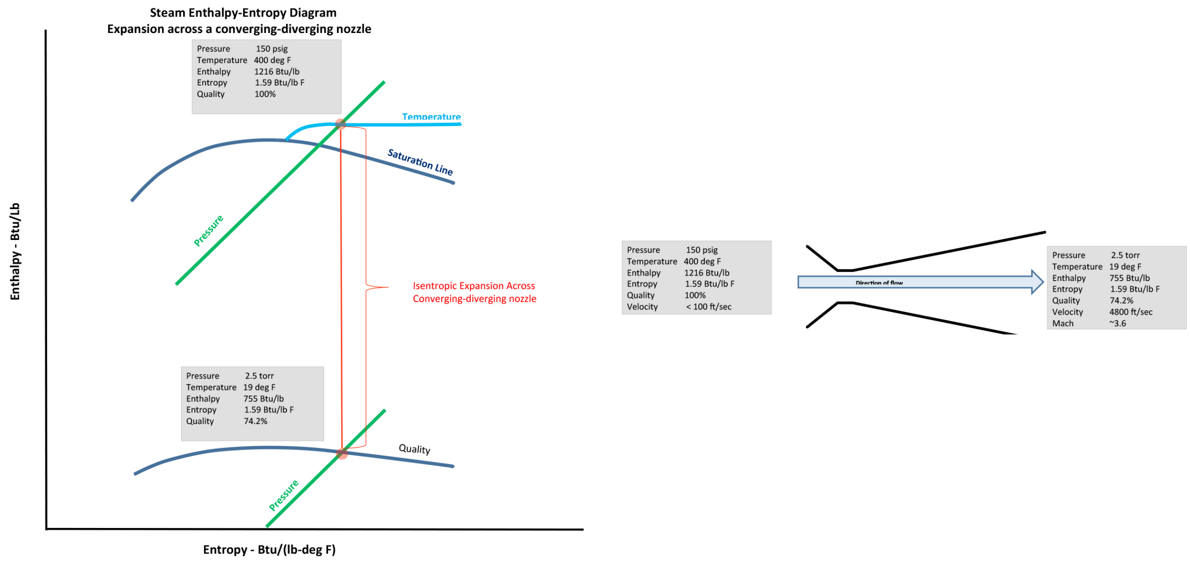


Figure 2. Expansion across motive steam nozzle.

nozzle is much less than the velocity exiting the nozzle; therefore, the velocity of the motive for supply conditions can be neglected. Equation 3 provides the derivation for, and how to calculate the velocity of, the exhaust of a motive nozzle.

Total enthalpy is constant across a motive nozzle:

$$h_0 \textit{ motive inlet} = h_0 \textit{nozzle exhaust}$$

$$h_{motive\ supply} + \frac{1}{2}\frac{Velocity_{motive\ supply}^{\ 2}}{g} = h_{nozzle\ exhaust} + \frac{1}{2}\frac{Velocity_{nozzle\ exhaust}^{\ 2}}{g}$$

$$Generally, Velocity_{motive\ supply} \ll Velocity_{nozzle\ exhaust}$$

$$Simplifies\ to, \quad Velocity_{nozzle\ exhaust} = (50100 * (h_{motive\ supply} - h_{nozzle\ exhaust}))^{0.5}$$

$$h_0 \textit{ motive inlet} = \textit{total enthalpy of motive supply}$$

$$h_0 \textit{nozzle exhaust} = \textit{total enthalpy at nozzle exhaust}$$

$$h_{motive\ supply} = \textit{motive enthaply at supply pressure and temperature, Btu/lb}$$

$$h_{nozzle\ exhaust} = \textit{enthaply at exhaust pressure and entropy, Btu/lb}$$

$$Velocity = \textit{Feet per sec}$$

It is now that sonic velocity comes into clear view. Note from Figure 2 that the velocity at the exit of the motive nozzle is 4800 ft/sec., or approximately Mach 3.5. Consider a case where an ejector is using 3#/hr of motive steam for each #/hr of load steam. In such a case, the mixture of motive and load remains supersonic at Mach 2.6. As the mixture moves along a second converging-diverging conduit (the diffuser), a shockwave is established when the ratio of downstream pressure and the suction pressure exceeds the critical pressure ratio. This is where the importance of sonic velocity comes to light. An acoustic wave travelling in the opposite direction of the fluid flow propagates upstream at the sonic velocity, which is slower than the supersonic velocity of the fluid. An acoustic wave, however, in subsonic flow, permits the fluid flow field to adjust to contractions or obstructions in the flow path because the acoustic pressure wave informs the flow fluid of the pending obstruction or change in direction. When flowing at supersonic velocities, the flow fluid cannot adjust to such contractions or obstructions because the flow is travelling faster than the acoustic pressure wave; therefore, the flow field cannot adjust, resulting in a shockwave forming that raises pressure and reduces volume with the flow passing through the contraction at sonic velocity. Figure 3 illustrates the pressure profile across a converging-diverging diffuser with pressure rise from a shockwave in the throat section. A digital image of an actual shockwave inside a glass diffuser is shown directly below the pressure profile.

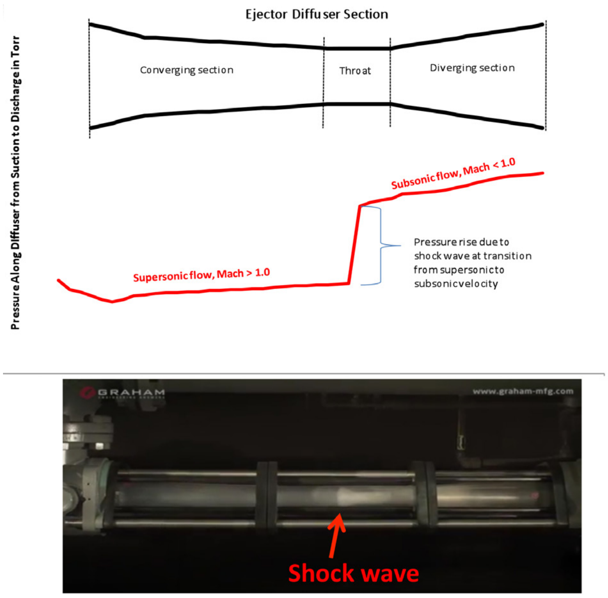


Figure 3. Pressure profile and shockwave that boosts pressure.

Ejector performance curve

Each ejector has a unique performance curve that defines the suction pressure the ejector will maintain as a function of suction load when supplied with design motive steam pressure – and the discharge pressure does not exceed its maximum capability. Figure 4 shows a typical ejector performance curve.

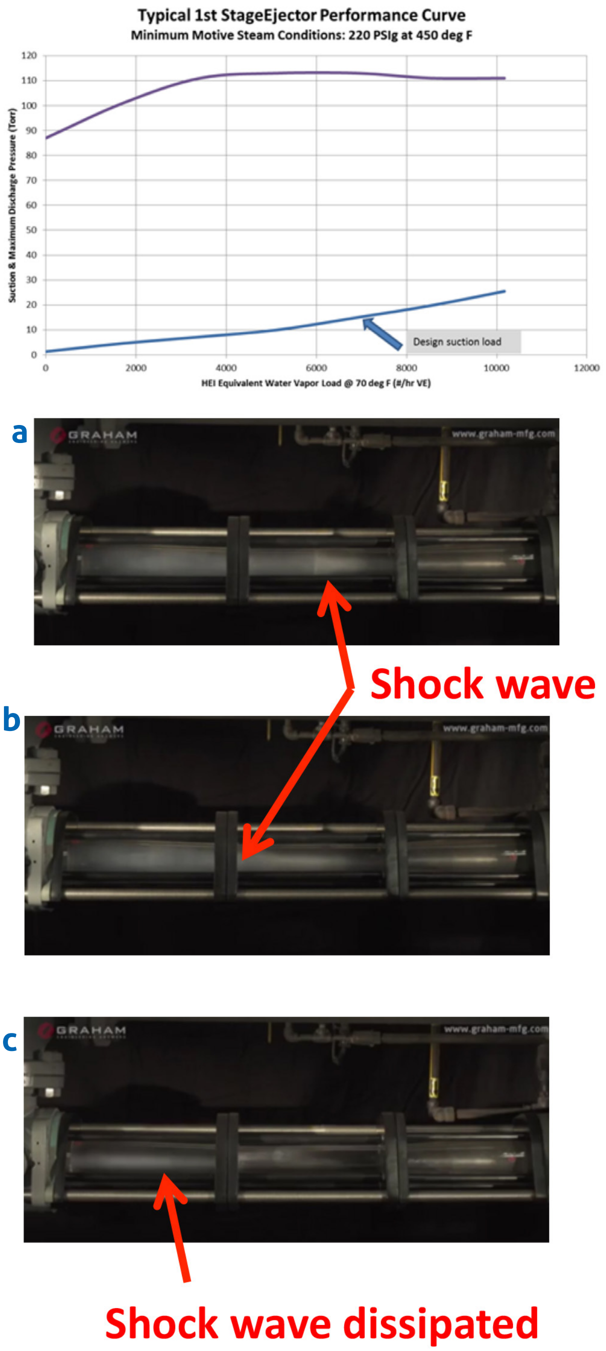


Figure 4. Shockwave position or formation, in relation to discharge pressure.

The performance curve informs the user of the following:

- At the design suction load of 7000 lb/hr, the ejector will maintain 15 torr suction pressure as long as the motive supply conditions are correct, or better, and the discharge pressure that the ejector is acting against is below its maximum discharge pressure.
- At 5000 lb/hr or 10 000 lb/hr of suction load, the ejector will maintain 10 torr or 25 torr, respectively.
- The maximum discharge pressure the ejector can act against is 111 torr, when steam pressure is at design conditions.
- Steam supply conditions should be 220 psig, or greater, and there should be a nominal temperature of 50˚F for superheat.

Variables that affect ejector performance

There are a few key variables that impact ejector performance. It is important to understand how these variables influence the formation and position of the shockwave. Videography illustrating the shockwave position readily conveys how performance deteriorates when discharge pressure exceeds the maximum capability of an ejector, motive supply conditions result in less energy provided for compression, there is mechanical damage to, or blockage within, the ejector, or the load conditions vary from the design. Liquid entrainment in the suction load is addressed separately to overview how it is detrimental to performance. Using the ejector performance curve from Figure 4, and considering three operating cases (a, b and c):

- Figure 4a: a well operating ejector at design loading is maintaining 15 torr suction and discharging to 105 torr. The shockwave is positioned in the middle of the diffuser throat. Motive supply conditions are according to the design.
- Figure 4b: discharge pressure is increasing due to the downstream intercondenser experiencing fouling, for example, resulting in an increase in condenser operating pressure. The increase in discharge pressure is moving the shockwave to the left, closer to converging section of the diffuser. The same will occur if motive pressure drops below design, or there is a mechanical issue limiting the amount of motive mass flow rate supplied to the ejector. The ejector is holding 15 torr, but discharge is bumping up against the maximum discharge capability of the ejector.
- Figure 4c: the shockwave is pushed outside of the throat and has dissipated due to high discharge pressure or insufficient motive energy supply. The discharge pressure exceeded the 111 torr maximum and the shockwave collapses. Suction pressure jumps to between 25 and 35 torr, and is surging. When a shockwave collapses, backstreaming into the process occurs, as flow momentarily reverses.

Liquid entrainment in process load

Steam jet ejectors, for most services, operate based on compressible fluid flow theory. There is a notion that liquid droplets in the suction load to an ejector, especially in crude oil vacuum distillation service, are unimportant and will not affect the performance of an ejector. Refiners in pursuit of improved yield may operate their vacuum distillation columns with vapour velocities at the higher end of the acceptable range, and may remove liquid entrainment reduction devices to lower pressure drop across the tower, thereby lowering the flash zone pressure. Consequently, liquid entrainment can be carried to an ejector with the overhead vapour load. In some instances, liquid entrainment can be quite substantial, and in the range of 50% of the vapour load or more.

The entrained droplets are in the 100 – 400 µm dia. range (0.1 – 0.4 mm). Droplets can meaningfully lower the discharge capability of the ejector, which increases performance risk or can increase suction pressure that will reduce yield for the refiner. If ejector discharge capability is lowered below the operating pressure of a downstream condenser within an ejector system, then a performance break occurs that sharply increases the vacuum column operating pressure, resulting in meaningfully lower yield for the refiner.

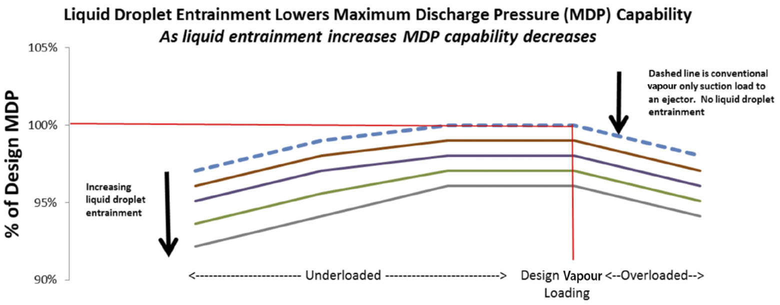


Figure 5. Droplet entrainment will reduce the maximum discharge pressure of an ejector.

Figure 6. From steam to ice.

Too much entrainment in the suction load will cause an ejector to perform poorly and exhibit unpredictable operating behaviour, where the ejector operates significantly off its performance curve.

The effect of increased liquid entrainment in the suction load to an ejector is shown in Figure 5. Where entrained droplets increase as a percentage of the load, the discharge capability of that ejector is progressively reduced. Therefore, a performance break or an ejector operating in a broken condition can occur as a result.

From steam to ice

Higher vacuum ejectors where suction pressure is below 5 torr require careful consideration. This is due to the fact that the triple point of water is 4.6 torr and 32˚F. At the triple point, liquid, solid and gaseous phases are in equilibrium. Below the triple point, a liquid phase cannot exist and deposition occurs, where the vapour phase will pass directly to a solid phase, or in reverse, sublimation occurs and the solid phase passes directly to the vapour phase. Motive steam, as previously outlined, expands isentropically across the steam nozzle from the motive steam supply pressure down to a pressure below the process suction pressure. As shown in Figure 2, 150 psig motive steam at 400˚F that expands across a converging-diverging nozzle down to 2.5 torr (0.048 psia) will exit the nozzle at a temperature of 19˚F, and will have a quality of approximately 74% (or it will be 26% ice crystals or liquid droplets). Liquid droplets exist due to a supersaturated condition caused by high velocities not permitting phase equilibrium to be achieved. At 19˚F, ice crystals form and aggregate within an ejector, blocking or disrupting flow. Due to such a cold temperature, the external temperature of the ejector body in the inlet section will condense humidity from the surrounding ambient air, leading to ice build-up on the ejector. Steam jackets or heat tracing is used to prevent the internal and external formation of ice. Figure 6 illustrates ice formation on the exterior of an ejector, and shows how ice can build up on the internals as well. A steam jacket is used to prevent ice formation in order to maintain proper operation of the ejector.

Mechanical damage

Process conditions can be corrosive, or motive steam quality resulting in moisture in the supply steam can be erosive, which leads to mechanical damage to an ejector and can disrupt performance. Furthermore, there can be blockage in the diffuser from ice or product formation, or in the motive supply lines that reduce motive mass flow rate to the ejector. Material selection, strong controls to ensure motive steam supply is not wet or overly superheated, as well as proper maintenance, are all essential for reliable ejector and ejector system performance.

Best practice for installation set-up

Each ejector should have pressure and temperature measurements or, as a minimum, connections that will permit field measurements on the motive steam supply line and on the suction and discharge lines. Figure 1 provides recommended best practices for instrumentation. These measurements are critical for effective performance analysis. When performance is not according to design, initial diagnostics will include a pressure and temperature assessment for each ejector.

Conclusion

Ejectors are found throughout the oil refining and chemical industries. They serve vital roles that support facility throughput, product quality, energy management and reliable on-stream performance. A deeper understanding of their performance characteristics is required to ensure plant operating objectives are met. The physics and thermodynamics behind the operation of steam ejectors may not be as well understood as other static equipment at an operating site. Performance troubleshooting and improvement can be challenging. It is always best to involve an ejector system supplier or vacuum technology company when specifying, procuring, installing, operating and assessing the performance of steam jet ejectors. They can be a 'black box', and flawed assumptions will lead to frustration and lost profits. HE

GRAHAM
ENGINEERING ANSWERS

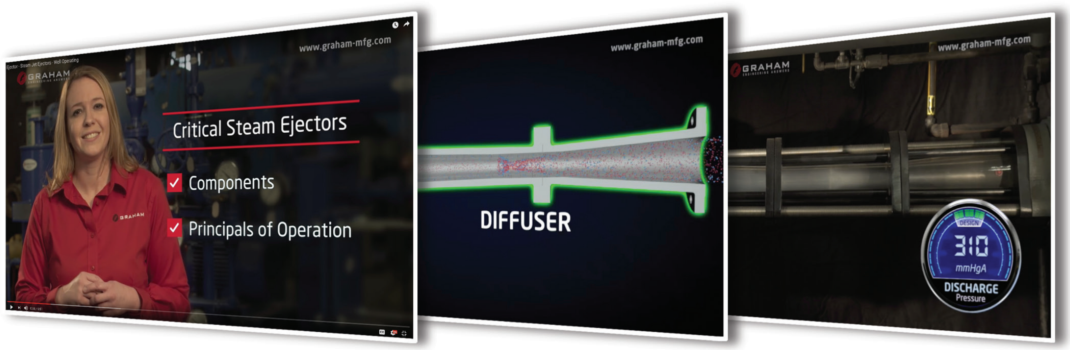
www.graham-mfg.com

Superior Vacuum Column Performance

Graham Ejector Systems. No Substitute for Proven Experience.

- Reliable flash zone pressure
- Successful global installations
- Trusted for over 8 decades
- Efficient energy consumption
- Technical and quality leadership
- Exceptional field service and support

Go to www.graham-mfg.com/ejector-videos to view our ejector performance videos



Graham Corporation, 20 Florence Ave, Batavia, NY 14020 585-343-2216 applicationengineering@graham-mfg.com