Choose the Right Vacuum Pump

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Several devices are available for producing vacuum at a chemical-process plant. Each has its own advantages and drawbacks

The need to operate under vacuum is widespread throughout the chemical process industries (CPI). Distillation, drying, flash cooling, stripping, and evaporation are among the unit operations that frequently take place at less than atmospheric pressure.

In many process applications, the overriding consideration is the amount of vacuum (or degree of evacuation) required. Of the five major types of vacuum producing devices discussed here, the ejector can achieve the greatest degree of evacuation: down to 5 micrometers of Hg absolute. Dry pumps and rotary piston pumps can each evacuate to 10 micrometers Hg; once-through oil pumps can reach 500 micrometers Hg; and liquid ring pumps can go down to 10 mm Hg.

Aside from its vacuum producing ability, each of the five types has its own set of attractions and drawbacks. Many of these depend on the particular application.

Ejectors are workhorses

The simplest and probably most widely used vacuum producer is the ejector (Figure 1). Sometimes called a jet pump, an ejector works by converting pressure energy of a motive fluid (which may be the same as or different from the process fluid) into velocity energy (kinetic energy) as it flows through a relatively small converging-diverging nozzle. This lowered pressure of the motive fluid creates suction in a mixing chamber, into which the process fluid is drawn from the vessel being evacuated. The process fluid mixes with and becomes entrained in the motive fluid stream. This mixed fluid then passes on through a converging-diverging diffuser, where the velocity is converted back to pressure energy. The resultant pressure is higher than the suction pressure of the ejector.

Ejectors use many types of motive fluid. Steam is the most common. Other popular choices include ethylene glycol, air, nitrogen, and vaporized organic solvents. To avoid contamination and other problems, it is important to choose a motive fluid compatible with the process fluid.

Ejectors offer a range of attractions:

- Simple design, with no moving parts and practically no wear
- Can be mounted in any orientation
- Can be fabricated of virtually any metal, as well as various types of plastics. The latter are usually fiber reinforced grades
- Lowest capital cost among vacuum producing devices
- Offers the largest throughput capacity of any vacuum producing device - can handle more than 1,000,000 ft^3/min of process fluid
- No special startup or shutdown procedures required
- Can handle condensable loads
- Simple repair and maintenance.

On the other hand, there are also disadvantages to ejectors:

- The requirement of a pressurized motive fluid
- The inevitable contamination of the motive fluid by the process gas, and vice versa
- Can be noisy; may require discharge silencers or sound insulation
- In most cases, the need for a cooling liquid source to condense the mixture of motive and process-fluid vapors

Ejectors are especially attractive when the process load contains condensable or corrosive vapors, very low absolute pressures are needed, or the vacuum producing capacity required is very large. However, these devices are not confined to such applications; they should also be evaluated, along with other options discussed below, in other process situations.

Ejectors also work well as boosters upstream of liquid ring pumps (below). This combination can minimize capital and utility costs with no sacrifice in performance.

As in any nozzle, the phenomenon known as critical flow can arise with an ejector. Roughly speaking, critical flow prevails when the discharge pressure is at least twice the suction pressure. Under these circumstances, a standing shock wave is set up.

A common misconception arises with regard to critical flow: that if the discharge pressure is reduced, the suction pressure of the ejector will decrease and thus a higher vacuum will be created. This is not possible, because the shock wave isolates the inlet conditions from the discharge conditions. An alternative way for the vacuum level of the ejector to be increased is by putting less load to it. Usage of ejectors throughout the CPI is wide. Examples include: vacuum distillation in petroleum refineries

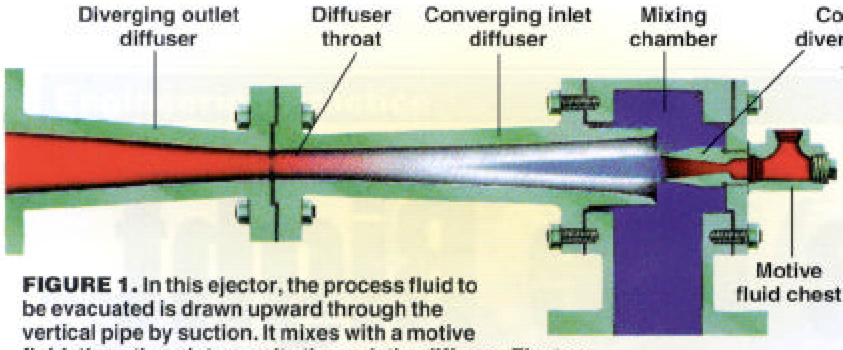


FIGURE 1. In this ejector, the process fluid to be evacuated is drawn upward through the vertical pipe by suction. It mixes with a motive fluid; then, the mixture exits through the diffuser. Ejectors are probably the most widely used vacuum-producing devices

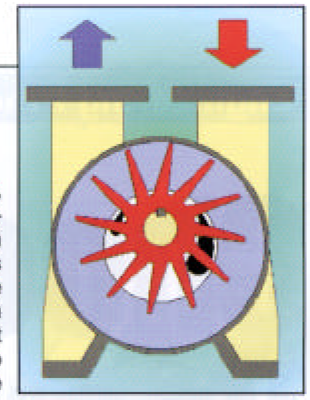


FIGURE 2. The liquid-ring vacuum pump carries a higher price tag than an ejector, but it costs less to operate

and chemical, plastics, pharmaceuticals and synthetic fibers plants; refrigeration at pulp and paper mills; drying in chemical and pharmaceutical plants; drying, flash cooling and refrigeration at food plants; and product degassing in steel mills. A related widespread use is condenser air venting at power plants.

Liquid ring pumps are cool

Another vacuum producing device that can evacuate vessels containing condensable or otherwise "wet" loads is the liquid ring vacuum pump (Figure 2). In its approximately cylindrical body, a sealant fluid under centrifugal force forms a ring against the inside of the concentric casing.

The source of that force is a multi-bladed impeller whose shaft is mounted so as to be eccentric to the ring of liquid. Because of this eccentricity, the pockets bounded by adjacent impeller blades (also called buckets) and the ring increases in size on the inlet side of the pump, and the resulting suction continually draws gas out of the vessel being evacuated As the blades rotate toward the discharge side of the pump, the pockets decrease in size and the evacuated gas is compressed, enabling its discharge.

The ring of liquid not only acts as a seal; it also absorbs the heat of compression, friction and condensation. In principle virtually any type of liquid can be used, so long as it is not prone to vaporization (and thus to cavitation) at the process conditions. Popular choices include water, ethylene glycol, mineral oil and organic solvents. Assuming that the evacuated process vapor does not react with or dissolve in the sealant liquid, contamination is minimized and the condensed process fluid is available for reuse in the plant.

The advantages of liquid ring vacuum pumps are as follows:

- Simpler design than most other vacuum pumps; employs only one rotating assembly
- Can be fabricated from any castable metal
- Minimal noise and vibration
- Very little increase in the temperature of the discharged gas
- Can handle condensable loads
- No damage from liquid or small particulates entrained in the process fluid
- Maintenance and rebuilding are simple compared to most other vacuum pumps
- Inherently slow rotational speed (1,800 rev/min or less), which maximizes operating life
- Can be started and stopped over and over
- Can use any type of liquid for the sealant fluid, in situations where mingling with the process vapor is permissible

The drawbacks of liquid-ring vacuum pumps are as follows:

- Inevitable mixing of the evacuated gas with the sealing fluid
- Risk of cavitation, which requires that a portion of the process load be noncondensable under the pump operating conditions
- High power requirement to form and maintain the liquid ring, resulting in larger motors than for other types of pumps
- Achievable vacuum is limited by the vapor pressure of sealant fluid at the operating temperature The liquid-ring pump is especially attractive when the process load contains condensable vapors, or if liquid carryover is present (due either to normal operation or process upsets), or if cool running operation is required due to flammable or temperature sensitive process fluids. However, these devices may also prove to be the best choice for other process situations.

For condensable process fluids, the choice between a liquid-ring pump and an ejector usually depends on the nature of the customer's business. Ejectors offer the lower capital cost, but the liquid-ring models are ordinarily less expensive to operate. Accordingly, for example, a customer with a ready source of inexpensive steam for use as motive fluid might favor the ejector.

One-stage (medium vacuum) versions of the liquid-ring pump can evacuate up to 20,000 ft^3/min. Two-stage (high-vacuum) versions evacuate up to 7,000 ft^3/min.

Like ejectors, liquid-ring vacuum pumps are widely employed in the CPI. They are found at petroleum refineries and petrochemical plants for vacuum distillation and vapor recovery, and as an adjunct to vent gas compressors. Chemical and pharmaceutical facilities employ them for distillation and drying; at pulp and paper mills, they are found for the priming of stock-handling pumps.

Plastic and synthetic-fiber facilities apply them for distillation and for venting extruder gases. They dry and flashcool a variety of food products. Among their environmentally related applications are groundwater remediation and sampling, and vacuum filtration of wastewater.

Dry pumps run cleanly

Unlike ejectors and liquid-ring pumps, dry vacuum pumps are devices that need no working fluids. Three types are available: the hook-and-claw, screw and lobe types (Figures 3, 4 and 5).

CONDENSERS LEND ENCHANCEMENT

In situations where the process fluid being evacuated consists largely or fully of condensable vapor, the performance and economics of a vacuum-producing system can be optimized by including a condenser. Indeed, the condenser by itself functions as an efficient vacuum-producing device. A conventional vacuum pump, as described in the main text of this article, is required immediately downstream to remove noncondensable gases, including air that leaks into the process system. However, the load on this pump is far smaller than it would be without the condenser.

For environmental and other reasons, the condenser of choice is usually a shell-and-tube exchanger. It can be configured for either shellside or tubeside condensation. In either case, the process-fluid pressure drop through the condenser must be low, to prevent overloading the downstream pump.

In that regard, a common mistake is to simply install a heat exchanger designed for liquid-to-liquid service in the same throughput range. Such exchangers always incur excessive pressure drop, due to the presence of baffles throughout the shell and the absence of any aircooling section. What's more, they usually lack enough surface area to serve for condensing.

When sizing a vacuum system with a condenser, the engineer must realize that for steady state conditions handling condensable vapors, the condenser reduces load to the downstream equipment. When this same system is used during startup, running on air only, the condenser cannot reduce the load to the downstream equipment. This startup condition may determine the size of the equipment or warrant a special startup procedure.

A well-written specification for a condenser includes the following information:

- Operating pressure and temperature
- Discharge pressure
- Mass flowrate, molecular weight and relevant chemical properties (such as corrosiveness) of each component in the process stream
- Type and inlet temperature of available cooling fluid

The choice as to type of condenser (fixed tubesheet, U-tube, removable bundle, other) and the materials of construction may be included in the specification, left to the equipment vendor, or discussed between the two parties.

These pumps work by either of two mechanisms, volumetric reduction or the mixing of lower-pressure gas with higher-pressure discharge gas (as in a Roots blower). Some types use a combination of both mechanisms, the particular combination depending on the pump manufacturer.

Unlike liquidring pumps, dry pumps normally run hot, because there is no liquid to absorb the heat of compression. This increases the temperature of the process gas. To counteract this, some designs provide for precompression by recycling discharged gas that has been cooled.

Advantages of dry-running pumps include the following:

- No contamination of evacuated gas, which thus can be recovered readily
- Due to lack of condensation (which is assured because the device runs hot), pump can be fabricated of standard, inexpensive cast iron
- Can discharge to the atmosphere

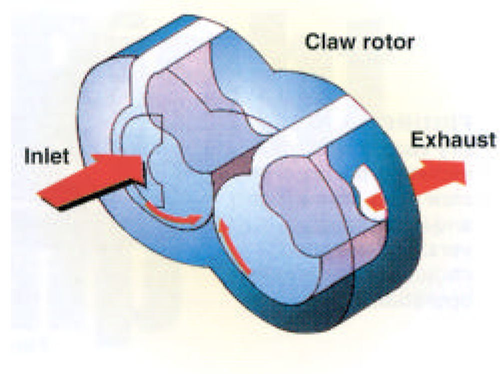
The drawbacks associated with dry pumps are as follows:

- Cannot handle particulates, nor large slugs of liquid
- May require a silencer
- May discharge gases at high temperatures, in some situations as high as 600°F
- In most models, dificult to repair or rebuild
- May require a gas purge for cooling, or to protect the bearings and seals from the process gas
- Limited choice of materials of construction for the pump
- Due to the high operating temperature, some process gases may have a tendency to polymerize

Dry pumps are more expensive than either ejectors or liquid-ring pumps. They should be used when contamination of the process fluid is to be avoided, when solvent recovery is the main objective, or when emissions must be particularly low. In cases where there is risk of liquid carryover from the evacuated vessel, the use of knockout pots, filters or other similar devices is required so the pump will not be damaged.

Single-stage dry pumps range in capacity from 70 to 1,500 ft^3/min. But when the pump is used as part of a two-stage system, capacities can be as high as 25,000 ft ^{s}/min.

In the CPI, dry pumps appear in pharmaceutical, fine-and-specialty-chemical and other chemical plants in conjunction with distillation, evaporation, and drying. They are wide spread in the semiconductor industry. And, food processors employ them for vacuum distillation.



The OTO option

A once-through-oil (OTO) vacuum pump is a sliding-vane type that uses once-through oil to seal clearances and lubricate moving parts. The vanes are in slots in a rotor, mounted eccentrically to the pump chamber.

As the rotor assembly rotates, centrifugal force pushes the vanes out of the slots and against the chamber walls, creating pockets whose size varies similarly to those of the liquid-ring pump. Because of this variation, suction draws process gas into the pump from the vessel being evacuated, and compression occurs as the vanes rotate toward the discharge side of the device, decreasing the area and forcing the gas and lubricating oil against the discharge valve. The discharge valve opens slightly above atmospheric pressure.

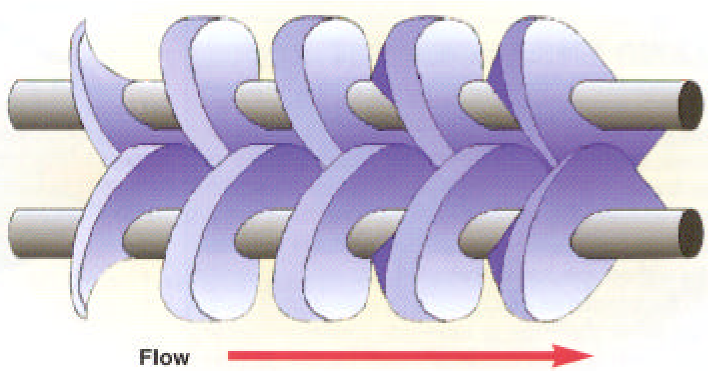
The attractions of the OTO pump include these:

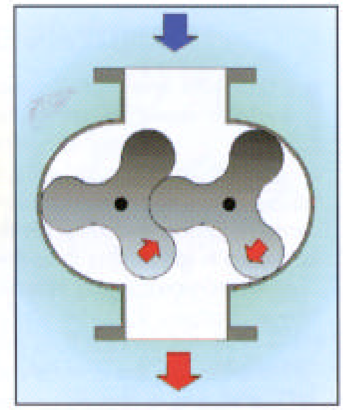
- Can handle acidic or otherwise corrosive vapors, because the once-through oil continuously flushes the vapors out
- Can be fabricated of cast iron
- Minimal vibration
- Can handle high inlet temperature (typically, up to about 250°F)

However, the OTO concept also has some disadvantages:

- Requires the use of immediately upstream knockout pots to prevent liquid from hitting (and thus breaking) the vanes
- Contamination of the discharged process gas by the oil (typically to the extent of 0.12 to 2 gal/d)
- Cannot handle particulates

FIGURES 3, 4, 5.
Dry vacuum pumps, including the hook-and-claw (left), screw (right) and lobe (far right) versions, are good choices for highly clean operations





- Solvent recovery not possible, due to oil contamination
- Costly to repair or rebuild
- Cannot readily accommodate condensable vapors
- Requires constant monitoring of the oil system

OTO pumps are usually found in pharmaceutical plants and fine-and-specialty-chemical plants, for drying, evaporation, distillation or other vessel evacuation tasks. Typical capacities are about *450* ft^{3}min.

In practice, the OTO pumps have often been misused, the aforementioned limitations being ignored. Today, this type of pump is being replaced by dry pumps, which incur lower lifecycle costs.

Rotary-piston models

A rugged type of vacuum-producing device is the rotary-piston vacuum pump. Its piston is attached to a cam that is mounted eccentrically to the main bore of the pump cylinder.

At the start of the cycle, the volume between the piston and cylinder increases as the shaft rotates the piston cam assembly. Gas is drawn in through a channel in the piston, until this volume is at its maximum. At that point, the pocket becomes sealed from the inlet as the inlet channel in the piston closes off. Lubricating oil helps seal the clearances.

The shaft then further rotates the piston-and-cam assembly, in a way that compresses the sealed-off gas against the pump cylinder and the discharge valve. The discharge valve opens when the gas pressure is slightly above atmospheric.

The gas and lubricating oil is then forced out and the cycle repeats itself.

Advantages are as follows:

- Minimal vibration, due to balanced configuration
- Rugged design, fostering long life
- Can handle small particulates

The disadvantages, many of them in common with those of the OTO pump, are as follows:

- Cannot handle liquids; requires the use of knockout pots
- The condensable vapors are not easily handled
- The discharge gas is contaminated with oil
- Solvent recovery not possible, due to oil contamination
- Some designs are noisy

The big attraction of the rotary piston pump is its ruggedness. Its major markets are outside the CPI: automotive, aerospace and heat treating.

Rotary piston pumps are often combined in series with another vacuumproducing device upstream, for greater pumping speeds and lower operating pressures. Singlestage capacities are in the range of *750* ft^3/min.

These vacuum pumps should be used when the process load is dry and contains only noncondensables. Contamination of the process gas cannot be avoided with this design. Furthermore, liquid slugs can damage the pump.

Preparing a good specification

Companies that manufacture and offer the complete line of vacuum-producing devices are in a particularly good position for choosing the best system for a given customer application. In any case, however, the vendor customer interaction is greatly enhanced if the customer prepares a detailed, well-written specification. Regardless of the type of vacuum-producing device, the vendor needs to know the mass flowrate and molecular weight of each component present in the process fluid to be evacuated, as well as the pressure and temperature at the inlet to the vacuum-producing system. If an ejector is under consideration, the customer should furnish the type, temperature, and maximum and minimum available pressure for the motive fluid, as well as the vapor pressure for each component in the process fluid. If the motive fluid is steam, its quality should be specified.

The pressure against which the device will discharge is important for all types of pumps covered in this article. If a liquid-ring pump is under consideration, the type and properties of the available sealant fluid should be indicated in the specification.

The available power supply is a key input for liquid-ring, dry, OTO and rotary-piston pumps. And for the last named three types, the customer must tell the vendor about possible liquid carryover, likelihood of polymerization or other solidification, and temperature limits due to autoignition or other phenomena.

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