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Revision Memo

- 12/01** Page 4 (Advantages/Disadvantages Table) Added Advantage of no separator needed for eliminating droplets in suction
Page 7 Added freezing moisture and jacketing considerations.

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SCOPE

This section presents background information on ejectors and procedures for calculating utility requirements of ejector systems. Since most plant systems use steam as the ejector motive fluid, steam jet ejectors are covered in greater detail.

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Matthews, John, *Low-Pressure-Steam Ejectors*, Chemical Engineering, June 22, 1987.

Newman, Eugene F., *How to Specify Steam-Jet Ejectors*, Chemical Engineering, April 10, 1967.

Power, Robert B., *Steam Jet Ejectors for the Process Industries*, McGraw Hill, Inc., New York, 1994.

Standards for Steam Jet Vacuum Systems, Fourth Edition, Heat Exchange Institute, Inc., Cleveland, Ohio, 1988.

DEFINITIONS

Booster - A term for ejectors applied for the high volume, low pressure stages of a multi-stage system up to the pressure level where condensers are effective with available cooling medium.

Capacity - The vapor-handling capability of an ejector system or ejector stage in mass flow units, typically pounds per hour (kilograms per hour) of dry air equivalent (DAE) at the design suction pressure.

Compression Ratio (or Pressure Ratio) - The ratio of the absolute pressure at the ejector discharge, P_2 , to the absolute pressure at the ejector suction, P_1 .

Critical (Critical Flow, Critical Stage) - A condition in which sonic or supersonic velocities exist in the ejector, identified by gas expansion and compression ratios which exceed about 2:1.

Entrainment Ratios - The molecular weight entrainment ratio is the ratio of the mass flow rate of gas entrained to mass flow rate of air which would be entrained by the same ejector operating under the same conditions. The temperature entrainment ratio is the ratio of the mass flow rate of air or steam at 70°F (21°C) to the mass flow rate of air or steam at a higher temperature that would be entrained by the same ejector operating under the same conditions.

Expansion Ratio - The ratio of the motive fluid inlet pressure, P_m to the entrained fluid inlet pressure P_1 .

Dry Equivalent Air (DAE) - The flow in lb/hr (kg/hr) of dry air at 70°F (21°C) which will produce the same suction pressure as the load mixture for which an ejector stage was designed. Heat Exchange Institute (HEI) standard correction factors for temperature and molecular weight are used to convert gas and vapor load mixtures to equivalent air loads.

MDP (Maximum Discharge Pressure) - In critical ejector stages only, the stage discharge pressure below which the ejector is always stable, operating on its basic performance curve. This limiting pressure varies with both the motive steam pressure and the load.

BACKGROUND

WHAT IS AN EJECTOR?

Ejectors are devices for raising the pressure of liquids or vapors which operate by entrainment of a pumped fluid into a high velocity jet of a higher pressure motive fluid stream. See **Figure 1** for a cross section view of an ejector. Ejectors have no moving parts, but are much less efficient than mechanical pumps and compressors and therefore are only applied where there are large quantities of motive steam or compressed gas available at low cost. Because they can handle the large volume flow rates at the low pressures required, they are commonly used on vacuum distillation towers and surface type steam condensers. They compress vapors which are not condensable at available cooling water temperatures to pressures at which they can be condensed or vented from the vacuum system. The following table summarizes some advantages and disadvantages of ejectors:

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BACKGROUND (Cont)**SUMMARY OF EJECTOR ADVANTAGES AND DISADVANTAGES**

ADVANTAGES	DISADVANTAGES
- Ejectors produce vacuum with no moving parts, no vibration, no high cost electricity, no bearing or seal problems, low noise level and minimum maintenance repair and operating attention. - They are explosion-proof, can be installed indoors or outdoors, have versatile mounting, long life and are easily cleaned. - Low equipment cost. - Low installation costs. - Higher reliability in severe services (relative to compressors). - Damage is easily repaired, and at relatively low cost. - No sealing chamber or stuffing box sealing required. - Requires no separator for eliminating droplets in suction flow.	- Very low efficiency (1 to 20%) when compared to mechanical compressors. - Running an ejector at motive steam pressure above design does not increase suction capacity; it just uses more steam. In fact, at motive steam pressures more than about 25% above design, capacity will actually start to decline due to "choking" in the venturi. - Ejectors are very sensitive to lower-than-design motive steam pressure. At pressures slightly below design, they simply do not operate properly. Significant reductions in both suction capacity and compression ratios may be expected. - Ejectors do not work efficiently on wet steam. They also fail faster, since wet steam erodes the steam nozzle and venturi. Water droplets moving at near sonic velocity can do substantial damage in a short time.

OPERATING PRINCIPLE

The principle governing ejector operation is that a high speed (reduced static pressure) fluid jet can entrain another fluid that is in contact with it, mixing the two fluids together. An ejector stage accomplishes this with three parts: a nozzle, a suction chamber, and a diffuser. **Figure 1** illustrates the relative pressures and velocities in a steam jet gas ejector. The steam nozzle allows expansion of the motive steam to a high velocity. This high speed jet, in contact with the gas to be compressed which enters the suction chamber, entrains the gas forming a mixture with high velocity and at the entrained fluid inlet pressure, P_1 . Compression of the mixture to discharge pressure, P_2 , takes place as the velocity energy is converted into pressure as the mixture decelerates through the diffuser.

CLASSIFICATION

Service Classification - Services to which ejectors are applied may be classified in the following ways:

- Continuous or Intermittent Operation** - Most process and machinery auxiliaries are continuous; startup evacuation is intermittent.
- Motive Fluid Employed** - Steam, process gas, air, liquid.
- Entrained (Process) Fluid** - Liquid or vapor.
- Condensing or Non-Condensing** - Continuous services almost always have condensers in the ejector system; intermittent services normally do not.
- Inlet Pressure Below or Above Atmospheric Pressure** - Most ejectors are applied in vacuum service. See [Section XI-B](#), *Compressor Type Selection*, **Figure 13** for application range of ejectors in vacuum service.
- Single Stage or Multistage** - Choice depends on pressure ratio requirement.

Ejector Type Classification - Ejector unit designs may be classified in the following ways:

- Motive Fluid** - Liquid or vapor.
- Entrained (Process) Fluid** - Liquid or vapor.
- Critical Flow or Subcritical Flow** through the diffuser throat.

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BACKGROUND (Cont)

APPLICATIONS

The table below arranges ejectors applications by motive fluid and load (suction) material.

MOTIVE FLUIDS	LOAD MATERIALS		
	VAPOR (STEAM, AIR, OTHER GAS)	LIQUID	SOLIDS
Vapor (Steam, Air, Other Gas)	Refrigeration, stripping, drying, compressor, "Btu controller," vacuum	Pump, heater, injector, sampling, mixing	Conveyor
Liquid	Vacuum, condenser, pump priming	Pump, mixing	Conveyor, mixing

The "vapor-vapor" ejector is the only type widely applied in refineries. The other types (vapor-liquid, liquid-liquid, and liquid-solid, etc.) are occasionally used for utility and special process purposes.

MOTIVE FLUIDS

Steam - Steam is the most common motive fluid used in process plant services. It has relatively low economic value, is readily available, easily recoverable by condensers, and compatible with most fluids to be compressed. Because of its condensibility, multistage continuous service applications usually have inter-condensers to remove motive steam (and any other condensible) between stages and thus reduce the load to subsequent stages. Clean dry steam is necessary for proper performance. More than 2 to 3% moisture in the inlet steam will reduce capacity and erode the nozzle excessively. Superheat insures dryness, but the energy of superheat is not converted to additional ejector capacity. The amount of superheat is critical for proper ejector design, since it influences the steam nozzle and throat design. An ejector designed for saturated steam will lose capacity if the steam is superheated, because the decrease in steam density reduces the mass that can flow through the fixed nozzle for given pressure conditions. Likewise, if less superheat than designed for is supplied, capacity will increase (5 to 10% maximum) until the diffuser throat becomes choked, reducing entrained gas flow rate.

Other Motive Fluids - Natural and refinery gases are occasionally used as ejector motive fluids when the mixture of motive and entrained gas is needed at an intermediate pressure level. For example, natural gas at high pressure can be used to compress tail gas or manufactured gas to an intermediate pressure level suitable for refinery fuel or public utility system distribution.

Compressed air is used as the motive fluid in portable utility ejectors, for general evacuation, and for pumping services, but is seldom applied in process services. Atmospheric air is used as the motive fluid in special single-stage ejectors which discharge into the inlet of a liquid ring vacuum pump. This allows operation at lower inlet pressures than are attainable with the liquid ring compressor alone with the available cooling water temperature. Water and other liquids can also be used to power vapor ejectors but at very low efficiency and for very low vapor flow rates.

PERFORMANCE CHARACTERISTICS

There is a distinct difference between the performance characteristics of critical flow ejectors and sub-critical flow ejectors. Ejectors designed for pressure ratios greater than about 2 will have critical flow (sonic velocity) through the diffuser throat (see **Figure 1**). For lower pressure ratios, subcritical (subsonic) flow occurs through the diffuser throat, allowing a wider range of capacity control. Critical flow ejectors are used in the vast majority of vacuum services to minimize the number of stages. Rated pressure ratios are usually kept between 6 and 10 for best efficiency, but can be as high as 20 for intermittent services with very low flow. Subcritical flow ejectors are normally applied with inlet pressures above 15 in. Hg abs (380 mm Hg abs), and are virtually always single stage. **Figure 2** illustrates the effect of pressure ratio on efficiency.

Figures 3 and 4 shows the typical performance curves for critical flow and sub-critical flow ejectors, respectively. In both cases, the capacity increases with increasing suction pressure. The discharge pressure behavior, however, is different for the two cases. For critical flow ejectors, the discharge pressure line rises progressively from zero flow (shut-off) to maximum flow and represents the maximum discharge pressure (MDP). Increasing the discharge pressure above the MDP causes a loss of performance. It may seem that a discharge pressure lower than MDP with a fixed inlet pressure should cause an increase in performance, but this is not the case for critical flow ejectors.

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BACKGROUND (Cont)

For subcritical flow ejectors, there are several methods of representing the ejector performance. The most common method is to present a single suction fluid curve for set discharge and motive fluid pressures, which do not vary with capacity. One variation is to present several suction performance curves at various motive fluid pressures, or at various discharge pressures.

The following table summarizes the effects of varying motive steam flow (via supply pressure change), inlet and discharge pressures and inlet flow rate for both types of vapor-vapor ejectors.

EFFECTS OF EJECTOR PERFORMANCE FOR CHANGES IN VARIOUS PARAMETERS

CHANGE	EFFECT ON PERFORMANCE	
	CRITICAL FLOW TYPE	SUBCRITICAL FLOW TYPE
Increased Steam Flow (5 to 10% maximum)	Increases maximum discharge pressure; practically no other change.	Reduces inlet pressure. Increases compression ratio. Alternatively, can operate at constant compression ratio and increased capacity.
Increased Intake Pressure	Reduces compression ratio; increases capacity.	Reduces compression ratio; increases capacity.
Increased Discharge Pressure	No change (until reaches breaking pressure).	Entire Family of curves moves with the discharge. Compression ratio remains practically constant.
Increased Capacity	Reduces compression ratio; increases inlet pressure.	Reduces compression ratio; increases inlet pressure.

MOLECULAR WEIGHT AND SUCTION TEMPERATURE EFFECTS

Figure 5 shows the effects that changing molecular weight has on the performance of critical flow ejectors. For the same discharge pressure and capacity, the suction pressure will increase with decreasing mol weight. Or for the same suction and discharge pressures, the capacity will increase with increasing mol weight. Another effect is the shape of the curve. The curves become steeper with lower mol weights, limiting the capacity range. For example, if an ejector designed to compress air is used to compress helium, the maximum capacity with helium may only be one third of the maximum capacity possible with air. The range of suction pressures in both cases may remain the same.

Figure 6 shows the effects that changing inlet gas temperature has on ejector performance. As the temperature decreases, the capacity increases. Or for the same discharge pressure and capacity, the suction pressure will increase with increasing suction temperature. The correlation is not very strong in that large changes in temperature produce small changes in suction pressure and capacity. For example, a 60% increase in suction temperature may only produce a 1% increase in suction pressure and a 10% decrease in capacity.

The curves in **Figures 5** and **6** are representations of the actual effects, but are not based on any correlations. They are given to aid in understanding the principles, but should not be used to estimate ejector performance.

OTHER PERFORMANCE CHARACTERISTICS

As the motive fluid pressure to an ejector is decreased (or discharge pressure is increased), a pressure level is reached at which flow becomes unstable. This level is termed the "breaking point." As the motive fluid pressure is increased again toward rated (or as discharge pressure is reduced), stable flow is restored at a somewhat higher pressure level called the "pickup point". For example, an ejector designed to operate at 150 psig (10.3 barg) motive steam may become unstable if the steam pressure falls to 130 psig (barg). The breaking point or break pressure is then 130 psig (barg). If the steam pressure needs to be raised to 160 psig (11 barg) to regain stability, that pressure is called the recovery or pickup pressure. Once the ejector has recovered, the motive fluid pressure can be reduced to the normal pressure. The breaking and pickup points are unique characteristics of each ejector and must be placed outside the specified operating range by the ejector vendor's design. For this reason, the values specified in the ejector service design for minimum motive steam pressure (and maximum superheat), and maximum discharge pressure are very significant.

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BACKGROUND (Cont)

To avoid instability in multi-stage ejector systems, the minimum inlet pressure to a stage must be below the maximum discharge pressure of the previous stage. Since the maximum discharge pressure can be increased by the increasing motive steam pressure (flow), a somewhat wider stable operating flow range can be obtained by raising the motive steam pressure above its normal level. However, the beneficial motive steam flow increase for this purpose is limited to 5 to 10%, since further increases will choke the diffuser throat, reducing the entrained gas flow rate.

- Expansion of motive stream through the ejector nozzle is almost isentropic; as a result, temperature of the stream exiting from the nozzle is usually quite low. Where the suction pressure of an ejector falls below 0.16 to 0.2 in Hg abs (4 to 5 mm Hg abs) this temperature is sufficient below 32 °F (0 °C) to freeze moisture in the suction gas and part of motive stream, thus forming an irregular cone of ice between the nozzle and diffuser. This obstruction will affect ejector stability between 5 mm pressure and shutoff (no load). If the nozzle tip and inlet diffuser section are heated to prevent ice from building up satisfactory operation at all pressures can be obtained. The usual way to do this is to steam jacket nozzle and diffuser.

Ejectors are normally designed for a stable operating range of 0 to 100% of design load for refinery services. However, to ensure this degree of operating flexibility, this requirement must be included in the Design Specification.

DESIGN CONSIDERATIONS

MULTIPLICITY, SPARING, AND EVACUATION

Vacuum pipestill designs usually include three installed 50% sized ejectors (two-stage condensing), one as 50% spare. In some instances two 100% ejectors are used to reduce piping and valve costs. The inter- and after-condensers (one each, unspared) are sized to handle the load of all three ejectors operating simultaneously.

On other services, evacuation time may dictate the sparing selection. To estimate time required for an ejector to evacuate a system from atmospheric pressure down to the design pressure, assume that the average air-handling capacity during the evacuation period is twice the design air-handling capacity. Assume also that air leakage into the system during evacuation is negligible. The approximate evacuation time is given by:

$$T_e = k \frac{V}{W_a} \quad \text{Eq. (1)}$$

- where:** T_e = The time to evacuate a system from atmospheric pressure to the design suction pressure of an ejector, min
 k = A conversion constant = 2.3 for Customary units (= 37 for Metric)
 V = The system volume vapor space, ft³ (m³)
 W_a = The ejector design air capacity, lb/hr (kg/hr)

If this approximate evacuation period is too long for a practical startup operation, it may be shortened by increasing the design flow rate of the last stage of the ejector, or by adding a non-condensing ejection "hogger" in parallel with the primary ejector. One non-condensing ejector may be used as an evacuator and emergency spare for serving several adjoining systems. The desired evacuation performance is specified by indicating the system volume, the desired evacuation time, and the absolute pressure to which the system must be evacuated.

STAGE CALCULATIONS

General - Stage calculations (see **Table 1**) are performed to determine the utility requirements of ejectors and condensers. Because most refinery applications use steam as the motive fluid, the examples that follow will do the same. Methods are presented for calculating the steam load requirement of ejectors, and the cooling water requirement of condensers. For simplicity, all hydrocarbons or other vapors are considered non-condensibles. If condensibles are present, these simple techniques will not apply. In order to perform the calculations, you must know the following:

- Motive Steam** - Pressure.
- Suction Fluid** - Inlet temperature, inlet and discharge pressures, gas composition and/or molecular weight, mass flow rate. If suction pressures and temperatures are unknown, consult **Table 3**. These temperatures are estimates that must be confirmed in the final design.
- Cooling Water** - Temperature and maximum temperature rise.

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DESIGN CONSIDERATIONS (Cont)

Ejector Calculation - Knowing the characteristics of the motive steam and suction fluid, the steam load requirement can be calculated by the following three steps:

1. Separate the suction fluid into two major components: (1) Steam, and (2) Air and other Non-Condensibles. If air is present and it is saturated with water, the amount of water vapor is determined from the following:

$$W_{ww} = \frac{P_{v,H_2O}}{P_1 - P_{v,H_2O}} \times \frac{W_a \times 18}{MW_a} \quad \text{Eq. (2)}$$

where:

- W_{ww} = The mass flow rate of water vapor in lb/hr (kg/hr)
- P_{v,H_2O} = The vapor pressure of water at inlet temperature in in. Hg (mm Hg), **Table 4**
- P_1 = The total inlet pressure in in. Hg (mm Hg)
- W_a = The mass flow rate of air and other non-condensibles in lb/hr (kg/hr)
- MW_a = The average molecular weight of air and other non-condensibles

2. Determine the Dry Air Equivalent (DAE) flow rate of the suction fluid. The DAE is determined from the following equation:

$$W_{DAE} = \frac{W}{R_{mw} R_T} \quad \text{Eq. (3)}$$

where:

- W_{DAE} = The Dry Air Equivalent mass flow rate in lb/hr (kg/hr)
- W = The mass flow rate in lb/hr (kg/hr) of suction fluid
- R_{mw} = The molecular weight entrainment ratio see **Figure 7**
- R_T = The temperature entrainment ratio from **Figure 8**

When calculating the total DAE, the two major components are considered separately. The "Air" curve on **Figure 8** is used to determine the R_{mw} for gases other than air and water. Therefore, the total DAE is given by:

$$W_{DAE,tot} = W_{DAE,st} + W_{DAE,a} \quad \text{Eq. (4)}$$

where:

- $W_{DAE,tot}$ = The total Dry Air Equivalent mass flow rate in lb/hr (kg/hr)
- $W_{DAE,st}$ = The steam or water vapor Dry Air Equivalent mass flow rate in lb/hr (kg/hr)
- $W_{DAE,a}$ = The air and other non-condensable hydrocarbon Dry Air Equivalent mass flow rate in lb/hr (kg/hr)

3. Calculate the motive steam load.

Mass flow of steam required is determined from the following equation:

$$W_m = W_{DAE,tot} \times R_3 \times R_{mw} \times R_T \quad \text{Eq. (5)}$$

where:

- W_m = The mass flow rate of motive steam, lb/hr (kg/hr)
- $W_{DAE,tot}$ = The dry air equivalent of suction fluid from **Eq. (4)**, lb/hr (kg/hr)
- R_3 = The ratio of steam flow to saturated water vapor flow, **Figure 9**
- R_{mw} = The molecular weight entrainment ratio of Steam = 0.81
- R_T = The temperature entrainment ratio from **Figure 8**

Typically, a 10% margin of safety is added to the calculation for motive steam load.

Multi-Stage Ejector Calculations - If the compression ratio of an ejector stage exceeds 10, it is more efficient to use a multistage ejector with an inter-condenser. Calculations for each stage of a multi-stage ejector are done in the same manner as single-stage ejectors. In addition, the following will be necessary to complete the analysis:

- **Interstage Conditions** - To find interstage pressures, take the square root of the overall compression ratio. Use 1.2 times this number for the compression ratio of Stage 1. Use **Table 3** to determine Stage 2 inlet pressure and temperature.
- **Interstage Flow** - If no inter-condenser is present, use **Table 3** to determine the Stage 2 inlet temperature and recalculate the $W_{DAE,tot}$ using **Eq. (4)**. Remember to include the motive steam load in the equation. If an inter-condenser is present, use **Table 3** to determine the Stage 2 inlet temperature and **Eq. (2)** to determine water vapor load. Use this water vapor load in **Eq. (4)** to recalculate $W_{DAE,tot}$. Assume that the condenser removes all other water vapor.

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DESIGN CONSIDERATIONS (Cont)

Condenser Calculations - Once the total motive steam load is known, the cooling water requirement can be calculated from the following equation:

$$Q_{cw} = W_{st} \frac{h_{lg}}{K_c \cdot C_p (T_2 - T_1)} \quad \text{Eq. (6)}$$

where:

- Q_{cw} = The cooling water requirement at condenser inlet temperature, gpm (m³/hr)
- W_{st} = The total steam load, lb/hr (kg/hr)
- h_{lg} = The heat (or enthalpy) of vaporization of steam. For approximation use 950 Btu/lb (2210 kJ/kg)
- K_c = The conversion from mass to volume flow = 495 lb/hr/gpm (988 kg/m³)
- C_p = The specific heat of the cooling water. For approximation use 1.0 Btu/lb-R (4.18 kJ/kg-K)
- T_1 and T_2 = Inlet and outlet cooling water temperatures. 30°F (17°C) is a typical temperature rise.

If the steam is superheated, more cooling water will be required.

INFORMATION REQUIRED FOR SPECIFICATION

Table 2 shows a typical ejector data sheet. The information required to specify ejectors is given below.

- Number of units required for normal operation and spares, if any.
- Entrained fluid inlet temperature; give range.
- Capacity: lb/hr (kg/hr) of each constituent identified by name and molecular weight (give average M for hydrocarbon mixture). Note if component is condensible or not with plant cooling water. Include physical properties and corrosiveness of uncommon gases. Specify stable operating range required.
- Inlet pressure: in. Hg (mm Hg) absolute to avoid interpretation error.
- Maximum Discharge Pressure psia [bar (a)] and Temperature limit, if any. Specify where these conditions are, e.g., at after-condenser outlet.
- Maximum cooling water supply temperature and maximum acceptable temperature rise.
- Steam Conditions: minimum expected pressure and temperature at ejector flange, as well as boiler or main line pressure and temperature (maximum). Specify range of superheat, if any.
- Type and number of condenser required: specify design features desired, including either barometric leg or condensate pump and their discharge conditions.
- Materials of Construction: Specify if manufacturer's standard materials are acceptable or list acceptable alternatives.
- Secondary or future requirements, if any, i.e., evacuation duty or foreseeable future requirements.
- Installation requirements, if any (mounting location, orientation, etc.).
- Accessories: Y-type strainer in supply line, silencer (specify that noise level must meet International Practices), etc.

