# Ejectors Give Any Suction Pressure

*Recent tests on multistage ejector systems will simplify your task of designing vacuum-producing equipment for any pressure.*

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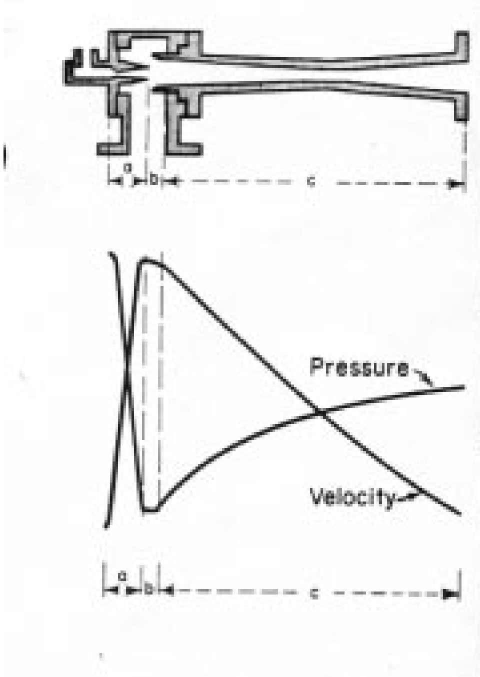
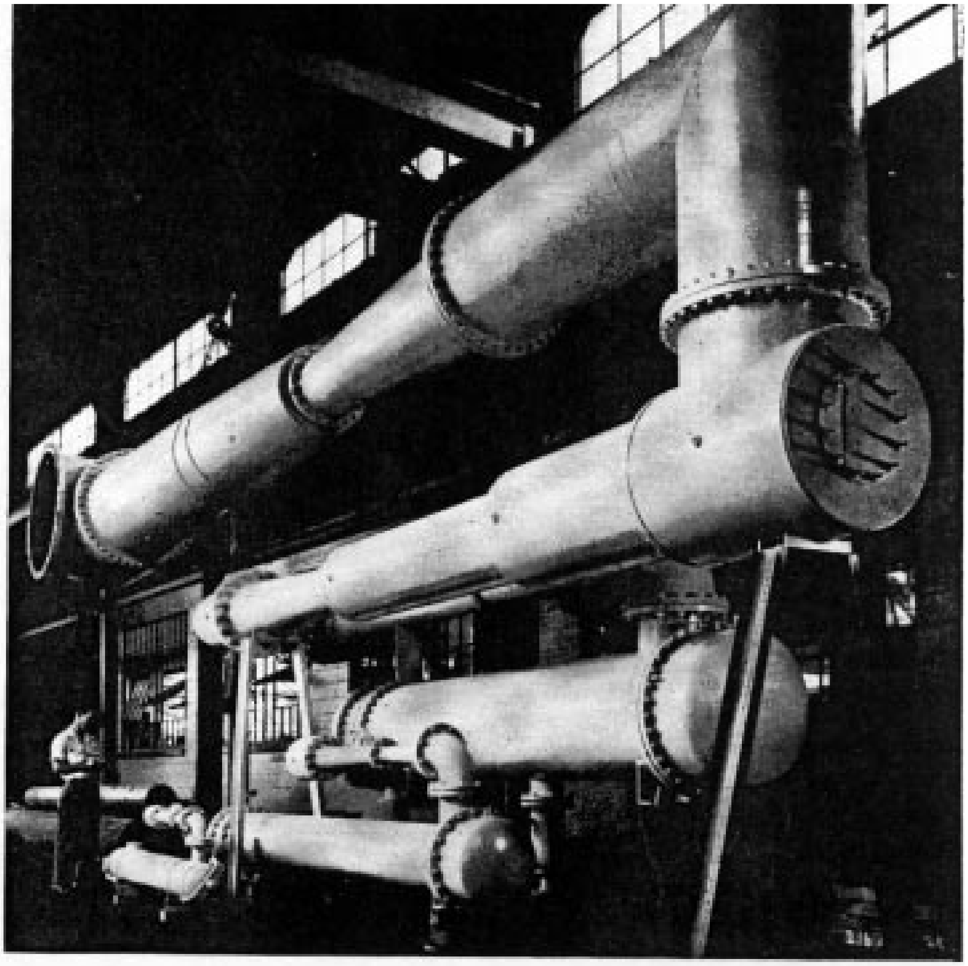
Because of overlapping performance, it's often a lengthy problem to arrive at the most economical design of an ejector. In practically every new application of high vacuum, we find it necessary to investigate thoroughly the many available means of producing vacuum to reduce equipment and operating costs to a practical and profitable level.

But the giant strides of technology have brought to light an entirely new concept in the study of vacuum-producing apparatus. Recent tests of 5-stage and 6-stage systems indicate that steam ejectors have carved a unique and popular place in industry where large volumes of gases must be evacuated—and they can produce almost any desired suction pressure.

In addition, by using only certain parts of a multistage system, one installation can serve the whole range of test conditions.

The simple principles on which ejectors operate and the almost universal use of steam and compressed air in plants of all kinds have given the ejector many advantages over other vacuum pumps. However, in spite of simple operating principles, the most economical design of an ejector is often a lengthy problem.





Among the variables that you should consider in selecting a particular design of steam ejector are:

1. Suction pressure required.
2. Steam available.
3. Water available.
4. Fluid to be evacuated.
5. Equipment cost.
6. Installation cost.

## LET'S DISCUSS PRINCIPLES

In order to show how these six variables affect the design of a steam ejector, let's discuss briefly the principles of ejectors.

All ejectors operate on a common principle. By means of a high-velocity jet of propelling steam, air or other fluid, a gas or vapor—or even finely divided solids—can be entrained and caused to flow at high velocity along with the motive stream.

Directing the combined stream into the diffuser section of an ejector converts velocity into pressure. In effect, the high-velocity combined stream pushes against the discharge pressure of the ejector and maintains a pressure difference between the suction inlet and the discharge of the ejector.

The line sketch above illustrates approximately a typical conversion of pressure to velocity in the nozzle of the ejector and the conversion of velocity into pressure in the diffuser.

In all flow processes there are energy losses. The ejector is no exception.

Let's suppose that the flow process within an ejector is 100% efficient. At 100% efficiency, it would be possible for an ejector handling no load to convert the energy of pressure of the motive gas to velocity in the nozzle and then convert this energy of velocity back to pressure in the diffuser so that the discharge pressure of the ejector would equal the initial pressure of the gas.

Such ideal flow processes can be approached in a well-designed flow section, where the expansion ratio of the gas is not too great. However, the jet velocity we achieve in this instance is not very high and there is relatively little velocity energy available to entrain a secondary gas.

Under normal circumstances the expansion process in the nozzle of a well-designed ejector is almost always a fairly efficient part of the overall flow process. So we get very small energy losses in the nozzle. However, as jet velocity is increased by altering the design, the task of efficiently converting velocity back into pressure becomes increasingly difficult. It is in this part of the flow process of an ejector that we lose some of the energy.

When we reach supersonic-flow velocities, shock waves are unavoidable in converting velocity back to pressure. These shock losses in the diffuser become more severe as the diffuser entrance velocity (velocity of compression) is increased. This, in turn, limits the discharge pressure to which the velocity energy can be converted.

Therefore, if we fix the discharge pressure—as it is for a single-stage ejector discharging to the atmosphere—there is a practical limit to the velocity of compression for which an ejector can be designed. And in the case of an ejector that is evacuating a closed vessel with no in-leakage, there is a limit to the absolute pressure that a particular number of stages will ultimately reach, even if we permit the ejector system to operate forever.

Suction pressure of an ejector handling a gas load is further affected by the surrender of part of the energy of the jet velocity to entraining (or accelerating) the load gas. This explains why the absolute pressure increases as the load to the ejector increases and why the number of ejection stages increases as the design pressure decreases.

## USE WATER TO CONDENSE

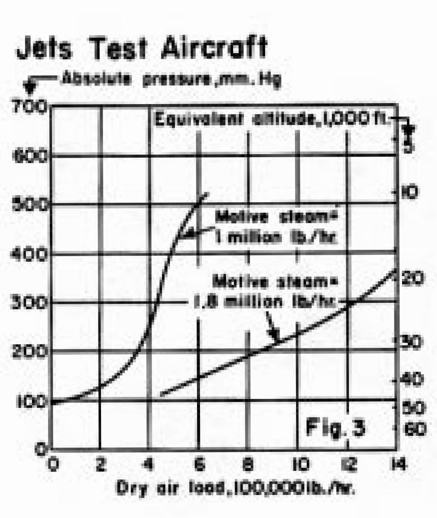
Where water is available at reasonably low temperatures, it's common practice to condense the steam from each stage of a multistage ejector in an intercondenser to reduce the load on the successive stage.

Such a design reduces the steam required to handle a given load as compared to a multistage noncondensing ejector, where each preceding stage discharges directly to the succeeding stage.

However, an intercondenser increases the initial cost of an ejector and the problem of selection is one of operating cost vs. initial equipment cost. Because every ejector application has its own economics, we can't set down a simple rule to guide the selection of the correct design. For a particular application, though, a buyer of ejectors often knows from experience the limitations on steam, water or money that he faces.

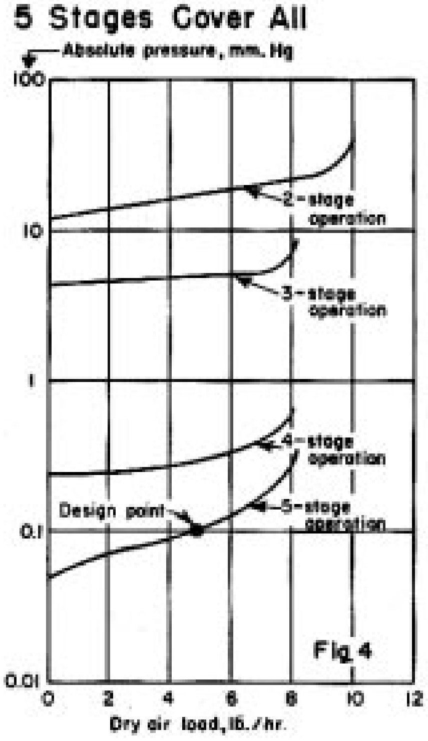
## A FAMILY OF DESIGNS

Since an ejector can be designed for high efficiency at some particular absolute pressure, each design will yield a different performance curve. Fig. 1 indicates the performance for a family of designs of 1-stage ejectors using the same quantity of steam in each design.



Jets Test Aircraft

Fig. 3



The envelope of this family of curves is the curve of all possible points of maximum efficiency for 1-stage ejectors. If we plot many graphs similar to that shown in Fig. 1 for many 1- to 5-stage ejector systems, the envelopes of the individual graphs will lead us to the overall plot, shown as Fig. 2 on the facing page.

Fig. 2 plots absolute pressure vs. air load for all the possible points of maximum efficiency covering the entire range of absolute pressures for which we usually use ejectors. The data are based on ejectors designed for maximum air-handling capacity at a particular pressure and include all of the most common ejector designs based on one steam consumption (100-psig. steam) and condensing water at an inlet temperature of 85° F.

We can see that as many as three noncondensing stages can be used practically. In 3-, 4- or 5-stage ejectors it's necessary to use non-condensing stages where the interstage pressure at which a condenser would have to operate would be too low for the water to condense the steam.

Fig. 2 permits a comparison of capacities of the various designs of ejectors that can be used for a particular suction pressure. For instance at 10 mm. Hg abs., four designs are available. They are:

- A 2- or 3-stage noncondensing system.
- A 2- or 3-stage condensing system.

From Fig. 2, we can see that a 2-stage noncondensing ejector would require about 9% more steam/lb. of air load than the 3-stage noncondensing ejector. However, the 3-stage ejector would cost considerably more than the 2-stage. Thus, there probably would not be enough advantage at 10 mm. Hg abs. to justify the additional initial cost of the 3-stage system.

The 2- and 3-stage condensing ejectors would require only 43% and 19%, respectively, of the steam required for a 2-stage noncondensing ejector. Of course, their initial costs would be higher and they need a supply of cooling water. If long periods of operation are required, however, the steam savings will undoubtedly more than make up for the difference in initial costs.

If we know the utility and equipment costs, it's a simple matter to calculate how many hours of operation will be required for the steam savings of the higher-cost designs to balance the increased initial equipment cost and increased cost of installation.

Installation costs can be an important consideration if steam and water lines must be extended any appreciable distance to the ejector, or if special structures must be erected to support the ejector. Ordinarily, a 1-stage ejector can be supported by the equipment on which it is installed. However, multistage ejectors with intercondensers require some kind of support if they are to be elevated, as they often are.

## WATER TEMPERATURE EFFECTS

If condensing water colder than 85° F. were used for our comparison in Fig. 2, all of the curves representing the performance of ejectors that require water would be shifted to the right, indicating an increase in capacity for these designs.

If water warmer than 85° F. were used, the shift in these curves would be to the left. And if the water temperature were high enough, some of the curves would move far enough to the left to disappear from the graph entirely.

The effect of water temperature is more critical on ejectors designed for low absolute pressures. For example, in a 4-stage ejector, the increase in capacity for 65°-F. water over 85°-F. water for a particular steam consumption will be greater at 1 mm. Hg abs. than at 4 mm.

## STEAM PRESSURE EFFECTS

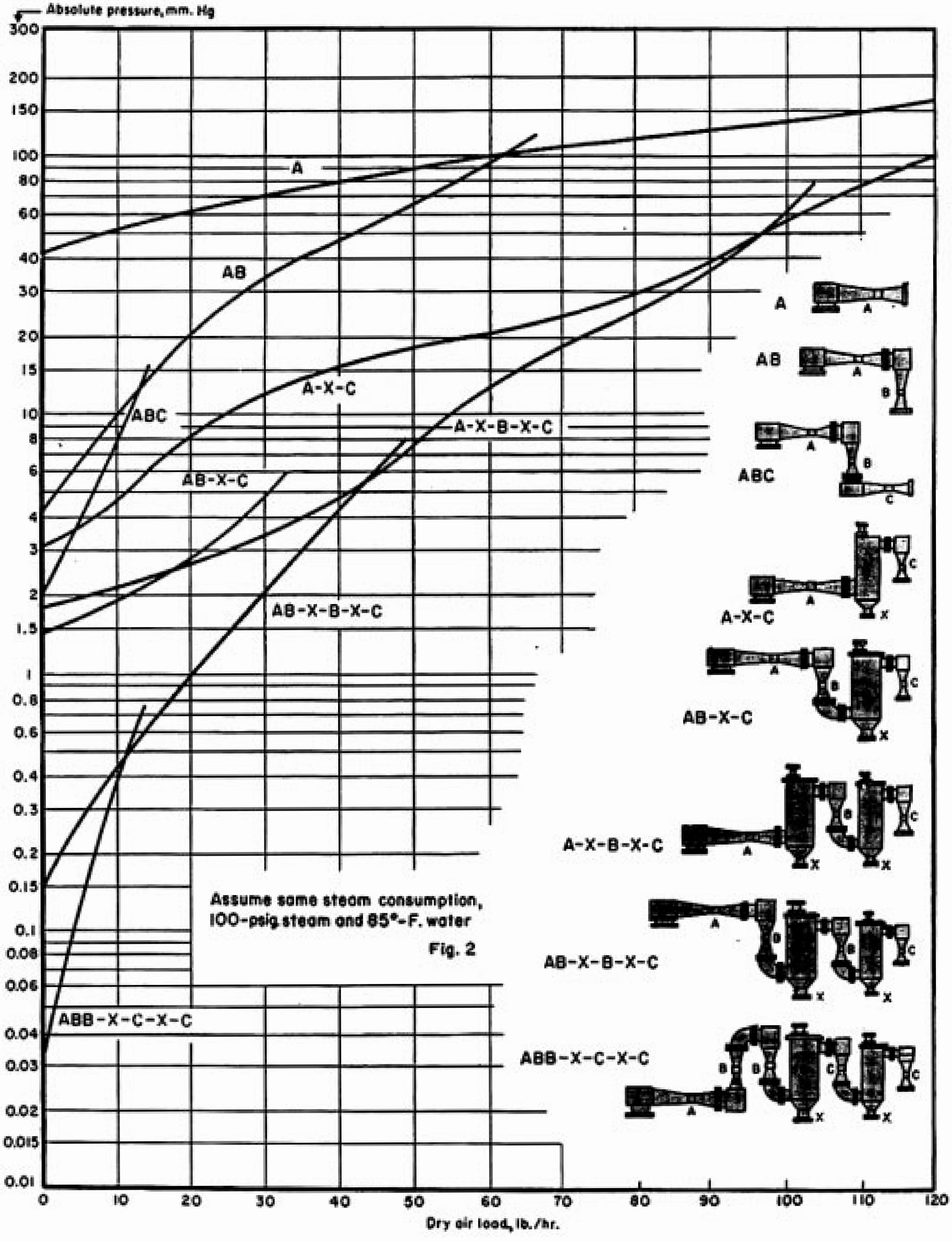
Steam pressures higher than 100 psig. will permit designing for a larger capacity for a particular steam consumption. A greater benefit from high steam pressures can be realized in 1- and 2-stage ejectors than in other designs.

The benefit from high-steam pressures becomes less as the absolute pressure for which the ejector is designed decreases. Single-stage ejectors designed for absolute pressures less than 200 mm. Hg abs. cannot operate efficiently on steam pressures below 25 psig. However, initial stages of multistage ejectors can often be designed to operate efficiently on steam pressures below 1 psig.

And it is not uncommon to use an extra stage for an ejector designed to operate on steam pressures as low as 15 psig.

It is very important that the steam used to motivate ejectors be at least dry-saturated steam. Small amounts of moisture can be removed successfully by using a good, properly sized steam separator which will remove 98 to 99% of the moisture entering the separator. Moisture in steam is usually difficult to detect without the careful use of a throttling calorimeter. Steam calorimeters are laboratory instruments and are seldom available in the field.

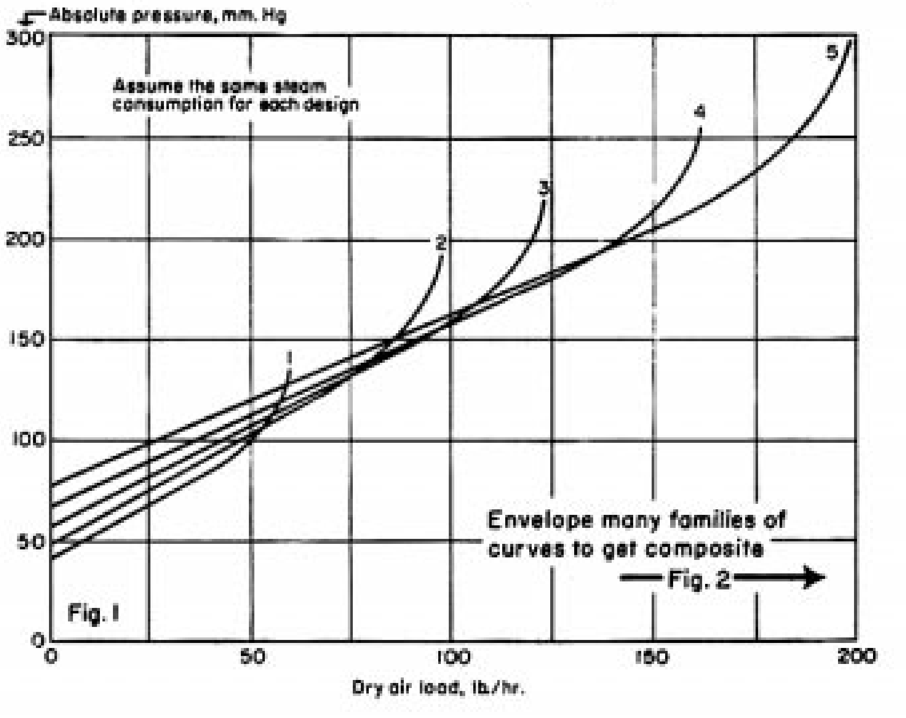
## Steam Jets Serve the Entire Pressure Range



Assume same steam consumption, 100-psig steam and 85°-F. water

Fig. 2

Performance Curves for a Family of Ejectors



Many an engineer has had difficulty proving or disproving that the quality of steam is affecting the operation of an ejector.

Steam separators are relatively inexpensive and should always be installed with an ejector wherever there is any possibility that the steam to the ejector contains moisture.

Steam lines from the boiler to the ejector should be insulated—especially where the length of piping is over 10 ft.—because if a boiler is generating steam that is just barely dry-saturated, it will take a relatively small heat loss to cause moisture to be present in the steam at the ejector.

## WHY USE INTERCONDENSERS?

Condensing ejectors are available in both surface or barometric (direct-contact) types.

We have not shown the economic considerations of water requirements on Fig. 2, but we should mention that the barometric intercondenser requires slightly less water to operate than the surface intercondenser.

Barometric intercondensers have these principal advantages:

- They cost less than a surface intercondenser designed for the same service.
- If used with a barometric leg, they don't need a condensate pump.
- They seldom require cleaning and can handle corrosive or tarry substances with relatively little wear or loss in efficiency.
- The vapors come in intimate contact with the condensing water in a scrubbing action that removes soluble vapors, gases and suspended solids from the noncondensables.

The disadvantages of barometric intercondensers are:

- Condensate mixes with the cooling water and cannot be recovered for use as hot, pure boiler feedwater.
- If a pump, instead of a barometric leg, is used to remove the water, it must handle the condensing water in addition to the condensate. This requires a larger condensate pump than for a surface intercondenser.

## HOW TO SELECT EJECTORS

By using Fig. 2 we can make the correct selection of a steam ejector to handle noncondensable gases. In cases where a portion of the load to the ejector is a condensable vapor, the data plotted on Fig. 2 are not applicable and it's necessary to analyze the particular operating conditions to determine the correct ejector design for optimum economy.

In some instances we can reduce the load to the ejector considerably by using a precondenser to condense a large portion of the vapors before they reach the ejector. Often the absolute pressure is too low to use a precondenser and it's necessary to compress or boost the vapors to a pressure where a large part of the condensing can be done in an intercondenser. This permits the use of small secondary ejectors to complete the compression of non-condensable vapors.

For a multistage ejector handling air or other noncondensable gases, there is a particular design that will require a minimum of steam and water for its operation. Using more water will not give any appreciable steam savings.

In cases where a large portion of the load is a condensable vapor, there is a range of steam and water combinations which can be designed for and the relative costs of steam and water will determine the best design. The cost of ejector equipment will usually not vary appreciably within the range of steam and water requirements possible. So the problem in these instances is one of economics of operation where the initial cost of the ejector equipment is fixed.

Performance of ejectors operating on fluids other than steam cannot be analyzed by using Fig. 2, since the thermodynamic properties of the motive fluid will vary the design of an ejector.

## OPERATING CHARACTERISTICS

Each stage of a multistage ejector has the same basic operating characteristics as a 1-stage ejector. Therefore, to understand the operation of a multistage ejector, we should first discuss how 1-stage ejectors operate.

Single-point design ejectors are most sensitive to changes in discharge pressure. If the discharge pressure of an ejector exceeds its minimum stable discharge pressure, the operation will become unstable and the capacity will no longer be a function of the absolute pressure. Stable operation can be attained either by increasing the steam flow or by decreasing the discharge pressure.

In a nozzle of a fixed design we have to raise the steam pressure to increase the steam flow. The minimum steam pressure at which the ejector regains stability is called the "motive steam pickup pressure." The motive steam pickup pressure is a direct function of the discharge pressure. At the higher discharge pressure, the ejector will regain its stability once the motive steam pressure is increased to the pickup pressure; but the absolute pressure for a particular load will be increased slightly from what it was at the lower discharge pressure.

For every discharge pressure in a single-point-design ejector there is also a minimum steam flow below which the operation will be unstable. For a nozzle of fixed design, we have to decrease the steam pressure to reduce the steam flow.

The maximum steam pressure at which the ejector becomes unstable is called its "motive steam break pressure." For a particular discharge pressure and load the motive steam break pressure is, of course, below the motive steam pickup pressure. At steam pressures between the break and pickup pressures, the ejector may operate stably or unstably depending on which direction the steam pressure is changing.

If the steam pressure is being increased from a point of instability, the ejector will operate unstably until the pickup pressure is attained; and if the steam pressure is being decreased from a point of stability, the ejector will operate stably until the break pressure is reached.

The terms "break" and "pickup" pressures are also used in reference to the discharge pressure of an ejector for the pressures at which ejector operation becomes unstable and stable, respectively. These critical discharge pressures are a function of the steam pressure and load for a fixed design.

Some ejector stages have no motive steam break and pickup pressures because of the low ratio of the discharge pressure to suction pressure over which they operate, or because they are designed to eliminate this characteristic. In these ejectors the capacity varies directly with steam pressure over certain operating limits.

Variations in ejector designs permit a variety of operating characteristics in ejectors. Certain of these may be essential to the success of an ejector for a particular application.

## SINGLE-POINT DESIGN

If only one load and vacuum are required for a particular application, single and multistage ejectors can be designed specifically for one condition. This saves steam.

Occasionally, however, single-point design ejectors are not always stable at very light loads or at loads slightly in excess of design load. An ejector of this design is not necessarily undesirable if the ejector always operates at the exact design conditions. This, of course, depends on whether or not it's possible to determine accurately the load on the ejector before it is designed.

Close designs can often result in substantial steam and water savings in large systems. However, we usually can't determine exact operating conditions prior to design. For this reason single-point designs are not in general use.

More often the design condition for an ejector can only be estimated approximately and we often arbitrarily select a design with a reasonable safety factor. Here the ejector is designed for stable operation at light loads as well as at its so-called design point to insure trouble-free operation if the load is more or less than that estimated originally.

A long range of stability from light loads to beyond design load will require more steam than the single-point design ejector. The greater the range of stability required, the more steam required. For the sake of steam and water economy, ejectors should not be designed for stability any farther in excess of design load than is deemed necessary for safe limits.

With low compression ratios, we can design an ejector that is inherently stable at light loads as well as at loads far in excess of design load. This requires little more steam than in the single-point design, and occurs when the suction pressure for which the ejector must be designed does not fall at the extreme low-absolute-pressure range of a particular ejector.

For instance, a one-stage ejector designed for 50 mm. Hg abs. would be more sensitive to off-design conditions than a 1-stage ejector designed for 100 mm. The 100-mm. ejector would have stable characteristics at light loads loads in excess of its design point with practically no increase in steam over the single-point design. In contrast, the 50-mm. ejector would need more steam over the single-point design to achieve stability at very light loads and loads in excess of its design load.

## MULTIPOINT DESIGN

Occasionally an ejector must operate alternately at two or more conditions of load and vacuum. Then we must design the ejector for the most difficult conditions (or the conditions that call for the largest ejector). The other conditions will then fall within the performance curve of the larger ejector.

An ejector of this type is sometimes considerably oversized for some of the required conditions in order to achieve the most economical design from the standpoint of initial cost. If operational economy is important at each of the conditions, it may be desirable to use two separate ejectors to achieve efficiency at both operating points.

It's possible in some applications to provide an ejector for two or more different operating conditions with maximum efficiency at each point by providing a steam nozzle or diffuser designed for each condition. In changing operations from one condition to the other, we only have to shut down the system long enough to change the nozzle or the diffuser.

Often, substantial steam savings can be realized without buying two ejector systems.

Designs of this kind have found applications in the recompression boosters for evaporators and large ejectors for high-altitude wind tunnels.

In certain applications ejector is required to meet a specific design curve. Then we sometimes must use considerably more steam than for a single-point design to produce the desired characteristic curve. At some point in the curve the ejector is, of course, relatively efficient and at either side of this high-efficiency point the ejector is relatively inefficient.

Ejectors of this type are used frequently by jet-aircraft-engine test laboratories where altitude conditions are simulated in a vacuum test cell. These test cells permit us to observe and measure the performance of an engine under the actual conditions that it will meet in the sky. Enormous ejectors have been built for various engine manufacturers to handle the combustion products from a jet engine at vacuum corresponding to altitudes as high as 100,000 ft.

At these altitudes the absolute pressure dwindles to 8 mm. Hg or less. Ejectors designed for these applications must cover a wide range of operating conditions with a minimum steam consumption.

Fig. 3 shows typical performance curves of some large ejectors now being used by aircraft companies to test engines at altitudes from sea level to 40,000 ft.

## USE ONLY SOME STAGES

It's possible to meet a large variety of operating conditions economically with multistage ejectors by operating only some of the stages at a time.

All ejectors have at least as many different performance curves as they have stages. For a particular stage to operate, all the succeeding stages must, of course, be operating also. Fig. 4 indicates a set of performance curves for a typical 5-stage ejector. By furnishing suitable automatic controls, practically all points within the envelope formed by these curves can be reached by the ejector. Thus, the ejector can cover an entire area of possible operating conditions.

On large ejectors, the cost of automatic controls may be paid for many times in steam savings.

Six stages of compression have lengthened the range of operation of steam ejectors down to absolute pressures as low as 5 microns of Hg (0.005 mm. Hg). Commercial designs are available and should often be used in place of other kinds of vacuum pumps.

Chief advantages of ejectors over other kinds of vacuum pumps are:

- Rugged and simple construction.
- They can handle enormous volumes of gases in relatively small sizes of equipment.
- Require less maintenance.
- Simple operation.

Other considerations, of course, may outweigh these advantages. Or perhaps the unavailability of a suitable motive fluid or water will rule out the use of an ejector for a particular application.

You'll need an overall picture of your requirements and utilities to select the best vacuum pump for your needs.

## ACKNOWLEDGMENT

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