

Fig. 1 .... Steam-Jet Refrigeration System with Surface Condenser

The design of an evaporator requires the water to be distributed in small droplets or thin sheets so that the main body of the water can attain equilibrium temperature by the time it reaches the bottom of the evaporator. The vapor space in the evaporator must provide volume for the vapor to freely separate from the liquid at a sufficiently low velocity to prevent liquid carryover into the booster suction. Spray systems are more susceptible to water carryover problems than cascade type systems.

It is important to keep pressure losses to a minimum between the point of vapor release from the water and the steam ejector suction, as any loss will require additional compression. A pressure loss of only 0.0056 psi (0.156 in. of water) will increase the required temperature lift by 1 F deg. This is a 2 percent lift increase in a typical application. As ejectors are inherently inefficient compression devices, it is important to minimize the compression work for maximum efficiency.

Evaporators can be further divided into two types:

1. The *open chilled water system* in which the refrigerant water from the evaporator is circulated directly to the cooling load, such as heat exchangers or other equipment which must be cooled.
2. The *closed chilled water system* in which the refrigerant water is recirculated within the evaporator over a coil or other heat transfer device through which is circulated another fluid (water or brine is commonly used) which never mixes with the refrigerant water, and which in turn is pumped to the cooling load.

The *open chilled water system* is more efficient since one less stage of heat transfer is required. Actually, for the same chilled water temperature the refrigerant water temperature (i.e., evaporator) can be 5 to 10 F deg higher using the open system.

Evaporator freeze-up may occur in steam-jet systems when certain control malfunctions occur. The open system has two distinct advantages in such a situation. First, the 5 to 10 F deg higher refrigerant water temperature means that the system has a greater safety margin above the possible freeze level. Second, should freeze-up actually occur, there is no danger of tube rupture which is certain to occur in the closed system. However, despite these disadvantages, some applications necessitate the use of a closed water system in order to isolate the chilled water system, due to some special process requirement.

The open system must be carefully designed to avoid leaks! It is recommended that the chilled water in open systems be pumped sufficiently above atmospheric pressure so that the water returning to the evaporator will be at 1 or 2 psig. This will prevent air leaking into the pressure side of the system and also will prevent vapor lock in the piping. The returning water is introduced into the evaporator through a back-pressure valve in such a case.

Although only one steam-jet ejector is shown in Figs. 1 or 2, more than one ejector can be used in parallel, discharging into a common condenser. A common evaporator cannot be used. Instead, an evaporator containing multiple compartments capable of being separated by water legs equal to the pressure difference between the evaporator and condenser must be employed.

Steam-jet Ejector

The steam-jet ejector is the heart of the steam-jet refrigeration cycle. The characteristics of this component have a major effect on the operating cost of the system and the size of both the condenser and condenser cooling water system.

A steam ejector is shown in Fig. 3. The terminology of the Heat Exchange Institute is given, but in addition, the sections are identified functionally. The high-pressure steam which is used to energize the ejector is called the primary fluid or motive steam. The induced stream, which is to be raised to a higher pressure level, is the secondary fluid and is often referred to as vapor. The motive steam is expanded through a converging-diverging nozzle to velocities of the order of 4000 fps. The corresponding nozzle pressure ratio is very high. For example, a nozzle expanding 150 psia motive steam to an evaporator pressure of 0.30 in. of mercury absolute (45 F chilled water temperature) will have a pressure ratio of about 1000. Nozzle pressure ratios of less than 200 are uncommon due to poor ejector efficiency when operating at low steam pressures. The high-velocity steam issuing from the nozzle entrains the water vapor in the suction chamber, and the two streams mix at constant momentum in the mixing section which is typically conical in shape. Theoretically, mixing is assumed to take place at constant pressure. This has been confirmed by test. For a typical steam-jet ejector in a refrigeration cycle, the mean velocity of the mixture will be supersonic (after mixing is complete at Station 1 of Fig. 3). In the constant area throat section this supersonic mixture undergoes a static pressure rise through a complex shock

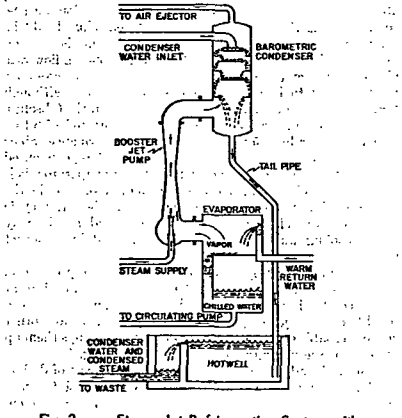

Fig. 2 .... Steam-Jet Refrigeration System with Barometric Condenser

wave in which the mixture velocity is decelerated from a supersonic to a subsonic velocity. This process actually takes some distance to be completed and in practice occurs between Station 1 and 2. The major portion of the ejector pressure rise actually occurs between these two stations. The subsonic diffuser is typical of all conical diffusers and continues to decelerate the mixture to the design exit velocity at Station 3.

Condenser

The condenser can be one of three basic types: (1) a conventional surface condenser, (2) an evaporative condenser, or (3) a barometric condenser.

The conventional surface condenser is commonly employed because of its compact size and ability to be located anywhere, including inside a building (Fig. 1). When a natural supply of cooling water is not available (i.e. river, well, ocean, etc.), it is necessary to employ a cooling tower. Use of a cooling tower will raise the condensing temperature above that which would be necessary if either an evaporative or barometric condenser were used. This means that the steam consumption will be correspondingly higher, and a larger surface condenser and cooling water system will be necessary.

The evaporative condenser contains tubes in which the steam from the ejector condenses. Forced air is drawn over the tube bundle upon which water is sprayed or otherwise distributed to produce the condensing effect through vaporization of water from the outer tube surface. Such condensers were used in railway car steam-jet refrigeration units of 5 to 7 tons capacity during the late 1930's and are now being made available in more modern, larger capacity units.[1] However, since such condensers cannot be located indoors, they are limited to outdoor installations. The evaporative condenser operates at a condensing temperature 3 to 8 F deg below that of a surface condenser with cooling tower and this in turn results in a favorable decrease in steam consumption.

The barometric or contact condenser is used to advantage in those installations which do not have space limitations (primarily vertical), and where it is economically feasible to treat the evaporator and boiler water on a once-through basis (Fig. 2). It has low first cost, and, since cooling water mixes directly with the steam to condense it, this results in a closer temperature of approach between the cooling water and the condensing temperature than would be found in either a surface or evaporative condenser. A barometric condenser will require an air ejector of considerably larger capacity to maintain condenser vacuum due to the additional air and noncondensable gas load that will be found absorbed in the cooling water that enters this type of condenser. In the majority of comfort air conditioning applications, barometric condensers are not employed, but they have found acceptance in industrial and other special applications.

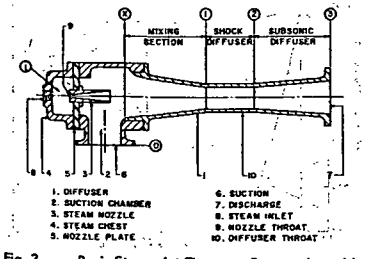

Fig. 3 .... Basic Steam-Jet Ejector or Booster Assembly

Air Ejector

The air or noncondensable gas ejector typically employs two small steam powered ejectors operating in series. An inter- and after-condenser is often employed to improve economy. In a tight system, an air ejector unit will have a capacity of 0.1 lb of air per ton of refrigeration. However, in many installations, particularly batch process applications, evacuation time of the system may be the governing factor in sizing the air ejector package.

Controls

The controls of a steam-jet unit are usually relatively simple as compared to other types of refrigeration systems. The evaporator water level and the condenser hot-well level are usually controlled by liquid level control devices such as float valves. A thermostatic control of the chilled water temperatures can be applied to operate the steam-jet unit (or in multiple ejector applications sequential activation) in an *on-off* mode.

DESIGN CONSIDERATION

Not much material on the physical design of efficient steam ejectors has been published. The majority of papers in the literature describe the best ejector of a particular investigative series, but unfortunately these have rarely, if ever, been as efficient as commercially available ejectors.[2,3,4] It is therefore undesirable to utilize or rely upon the design data generally found in the literature as a basis for an efficient ejector design. Nevertheless, much valuable work is recorded in the literature, and this contributes toward a better understanding of ejector design problems. The reluctance of ejector manufacturers to publish design data is understandable, since these concerns have evolved their designs through decades of costly experimentation. Only through relative secrecy can they realize a return on the investment required to obtain their knowledge. This implies that ejector design is more of an art than a science and this is, in fact, the situation at the moment. A major contribution to the science of ejector design has been the paper by Keenan, Neumann, and Lustwerk.[5] While this is a one-dimensional ideal analysis, it is very useful in describing a logical mathematical model of ejector operation.

Nozzle

The motive steam nozzle has a characteristic convergent-divergent shape. Its throat is sized to give the desired steam flow at the design inlet steam conditions. The nozzle's divergent section is typically conical in shape and the theoretical area ratio (cone outlet area to the throat area) is found through conventional supersonic flow equations.[6] The cone angles (total included angle) employed in the divergent nozzle cone range from 8 to 15 deg, with 10–12 deg being most common.

The theoretical area ratio and an assumed design divergent cone angle will define the theoretical length. However, experience has shown that in practice the cone length at the design cone angle should be reduced to 70–80 percent of the theoretical length for a broader efficiency characteristic of the ejector. This arises from the necessity of the ejector to operate at off-design conditions. It has been found[2] that it is more efficient to operate the ejector when the last portion of the expansion process in the divergent nozzle section takes