cylinder. Compressor cooling is highly desirable as a method of reducing power consumption.

Influence of Superheating and Subcooling

The most common departure from conditions of the simple saturation cycle is that resulting from admission of superheated vapor to the compressor. Thermodynamically, superheat is undesirable because the enthalpy increase required to compress a vapor through a given pressure range increases with superheat. Further, superheated vapor leaving an evaporator is usually an indication that the suction pressure is lower than necessary. Under practical operating conditions, however, superheat is almost universally used as a

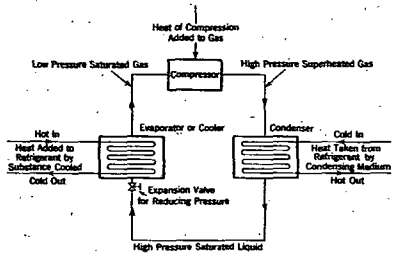


Fig. 3 . . . . Mechanical Refrigeration System

means of assuring complete vaporization of the refrigerant going to the compressor. With modern compressors operating at high speed, and with relatively small clearance space, it is particularly necessary to avoid admission through the suction valves of liquid refrigerant.

Another common departure of actual systems from the simple saturation cycle occurs because of subcooling of refrigerant in the condenser. Thermodynamically, such subcooling is advantageous since it increases the refrigerating effect without affecting the unit energy requirements of the compressor. Further, it can be shown that for a fixed ratio of condenser cooling water to refrigerant circulating rate, the total compressor power requirements will be greater when operating at simple saturation than when operating with maximum subcooling. What is even more surprising is that condenser pressure may be lower for the subcooling cycle than for the saturation cycle. This condition results from the fact that, for the same capacity on a heavily loaded condenser, the refrigerant flow rate is less when there is subcooling.

Because of the advantages attendant upon the use of subcooling, many methods are in use for obtaining some subcooling effect outside of the condenser. One common procedure is to use the cold vapor leaving the evaporator to cool the liquid flowing from condenser to expansion valve.

Another somewhat unusual subcooling cycle allows cold refrigerant from the downstream side of the expansion valve to cool liquid refrigerant from the condenser down to the evaporator temperature. Fig. 5 shows the pressure-enthalpy diagram for a typical refrigeration cycle operating with both subcooling of the refrigerant from the condenser and superheating of the refrigerant leaving the evaporator.

Complex Refrigeration Cycles

The preceding sections have dealt only with refrigeration systems in which there is but one evaporator; compression is accomplished through but a single stage, and expansion proceeds through a single expansion valve. In large systems or in low-temperature systems in which the compression ratio is high, the compression process can be carried out in stages, with the refrigerant passing through several cylinders arranged for operation in series. The thermodynamic advantage of such compound compression arises from the fact that intercoolers can be placed between the stages of compression to extract heat from the vapor, and thereby cause the overall compression process to approach more closely the ideal condition of isothermal compression. Essentially, such intercoolers serve the same purpose as a cooling jacket, but with greater effectiveness because of the more satisfactory heat-transfer conditions.

In the simple saturation cycle the saturated liquid entering the expansion valve commences to vaporize as soon as its pressure starts to drop. The vapor produced during the expansion process has no further use, in terms of refrigerating effect, since it has already picked up its latent heat of vaporization as a result of heat which it has extracted from the unvaporized residue. Thus the instant such vapor forms, its usefulness is at an end, and to allow such material to undergo a further drop in pressure is uneconomical. With compound compression, there is at least one intermediate pressure at which flash vapor can be extracted. In such cases several expansion valves can be utilized with all of the refrigerant from the condenser passed through a first expansion valve to the higher suction pressure, and the flash vapor then extracted and returned to the condenser through the high compression stage. The remaining refrigerant can then pass through a second expansion valve where the pressure is dropped to that corresponding to the low-pressure evaporator. The number of expansion valves is limited by the number of stages of compression.

Further cycle complications may arise if more than one evaporator is to be operated with a single compressor, and particularly, if the pressures in these evaporators are to differ. The most common solution is to operate the compressor at the suction pressure of the lowest pressure evaporator, and to equip all other evaporators with back-pressure regulating valves or throttling devices between the evaporator and the compressor suction.

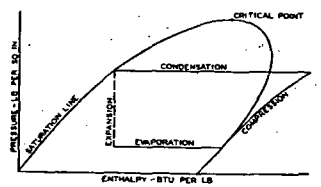


Fig. 4 . . . . Pressure-Enthalpy Diagram for Simple Saturation Cycle

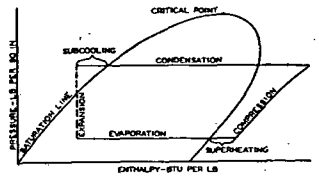


Fig. 5 . . . . Pressure-Enthalpy Diagram for Refrigeration Cycle with Subcooling and Superheating

The Air-Cycle System

Fundamentally, the air cycle' is essentially the same as the vapor cycle. Compression is accomplished by a reciprocating or centrifugal compressor, and, since there is no change of phase of the refrigerant upon expansion, an *air cooler* replaces the condenser, and a *refrigerator* replaces the evaporator. Although some cooling would result from the expansion of the gas through an ordinary expansion valve, a much greater drop in air temperature is accomplished if the expansion is controlled to approach the isentropic by replacing the valve with an expansion engine or turbine. Furthermore, the work recovered by such an expansion engine can be utilized to supply part of the work of compression or to drive other devices.

The Steam-Jet System

The *steam-jet system*, under certain circumstances, is desirable for use in air conditioning.' Steam supplies directly the power used for compressing the refrigerant, thus eliminating the losses connected with other methods of supplying energy. As the compression ratio between the evaporator and condenser under normal circumstances is large, the mechanical efficiency of the equipment is somewhat lower than that of the positive mechanical type compressor. The condensing water requirements are considerably greater, as both the refrigerant and the impelling steam must be condensed.

The steam-jet system functions on the principle that water under high vacuum will vaporize at low temperatures. Steam-jet boosters or compressors of the type commonly used in power plants for various processes,' will produce the necessary low absolute pressure to cause evaporation of the water.

A diagrammatic representation of a typical steam-ejector water-cooling system is shown in Fig. 6. The figures correspond to an average representative system. The water to be cooled enters the evaporator and is cooled to a temperature corresponding to the vacuum maintained. Because of the high vacuum, a small amount of the water introduced in the evaporator is flashed into steam. As this requires heat, and the only source of heat is the rest of the water in the evaporator tank, this other water is almost instantly cooled to a temperature corresponding to the boiling point determined by the vacuum maintained. The amount of water flashed into steam is a small percentage of the total water circulated through the evaporator, amounting to approximately 11 lb per (hr) (ton of refrigeration developed). The remainder of the water at the desired low temperature is pumped out of the evaporator and used at the point where it is required.

The ejector compresses the vapor which has been flashed in the evaporator, plus any entrained air taken from the circulated water, to a somewhat higher absolute pressure. The vapor and air mix with the impelling steam on the discharge side of the jet, and the total mixture then passes from the ejector into the condenser.

The slight amount of air which may be entrained in the cooled water is removed by a small secondary ejector that raises the pressure sufficiently so that the air can be discharged to the atmosphere. A secondary condenser is then necessary to condense the steam in the secondary jet.

While a single booster of smaller than 15 tons capacity is difficult to build, steam-jet vacuum-cooling units have been built for as small as 5 to 6 tons capacity. They can readily be built for steam pressures of from 5 to 200 psig, and condenser water temperatures as high as 90 F. The

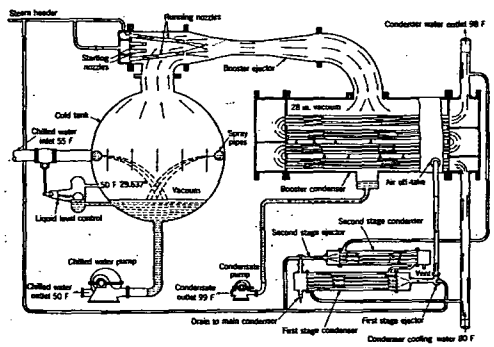


Fig. 6 . . . . Diagrammatic Arrangement of Steam-Jet Vacuum-Cooling Unit

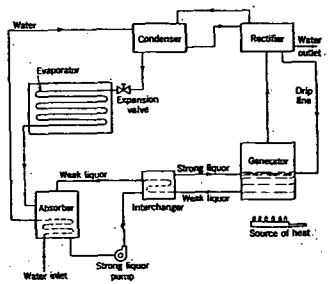


Fig. 7 . . . . Closed Absorption System