function to extract heat from the outdoor air.[37] The same surface may then be employed as a condenser using outdoor air as a heat sink for cooling. The refrigeration circuit employed may resemble that shown in Table 1 for an earth-to-air heat pump.

An indirect-type system employs another fluid, either water or air, which is circulated through the solar collector. When air is used, the first system shown in Table 1 for an air-to-air heat pump may be employed, the collector being added in such a way that: (1) the collector can serve as an outdoor-air preheater, (2) the outdoor-air loop can be closed so that all source heat is derived from the sun, or (3) the collector may be disconnected and the outdoor air used as the source or sink.[38] When water is circulated through the collector, the heat-pump circuit may be of either the water-to-air or water-to water type[39] illustrated in Table 1.

On all heat-pump systems employing solar energy as the only heat source, either an alternate heating system or a means of storing heat is required during periods of insufficient solar radiation. Heat storage is discussed in a later section of this chapter.

PERFORMANCE CHARACTERISTICS

Temperature Levels

Temperature differences are required to transfer heat from the heat source to the evaporating refrigerant of a heat pump, and similarly from the condensing refrigerant to the heating fluid. Hence, the total temperature lift of the refrigeration system must be increased over that represented by the difference between the heat source and sink temperatures.

Fig. 2 illustrates typical temperature levels for both heating and cooling operation. Specific heat pumps may vary somewhat from the temperature levels shown, depending on their design and specific conditions of operation. Equation 2 defines the coefficient of performance (CP) of a Carnot cycle heat pump. Applying the given relationships with the evaporator and condenser temperatures illustrated in Fig. 2 yields the coefficient of performance (CP) for a Carnot cycle heat pump shown in Fig. 3. An actual heat pump will, in a rough approximation, be about 50 percent as efficient as a Carnot cycle heat pump and will have a coefficient of performance dependent on temperatures, as illustrated in Fig. 3.

System Balance

The performance characteristics of a heat-pump system can be predicted by evaluating and combining the performance characteristics of its individual components.[40] Data available from component manufacturers may be shown as in Fig. 4.

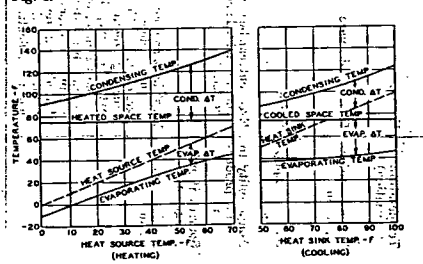


Fig. 2 .... Heat-Pump Temperature Levels

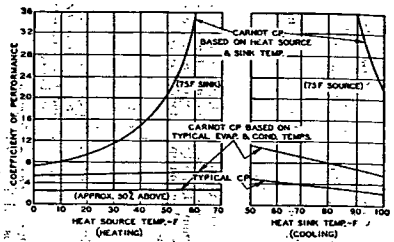


Fig. 3 .... Variation of Coefficient of Performance with Temperature

The conditions of system balance can be established by the following procedure:

1. Choose a combination of evaporator refrigerant temperature t_e and condensing temperature t_c.
2. Determine the compressor refrigerating effect from performance curves similar to *A* of Fig. 4.
3. Determine the compressor power input P_a in kilowatts from curves similar to *B* of Fig. 4.
4. Determine the condenser capacity from

$$Q_c = Q_e + 3413\ P_a - Q_{ac} \qquad (1)$$

where

Q_c = condenser capacity, Btu per hour.
Q_e = compressor refrigeration effect (evaporator capacity), Btu per hour.
Q_{ac} = heat loss from compressor, Btu per hour. (Q_{ac} may have to be approximated if unavailable from compressor manufacturer. For many compressors, Q_{ac} is negligible.)

5. Plot Q_c obtained from Equation 1 on a chart similar to *C* of Fig. 4. (See Fig. 5.)
6. Select other condensing temperatures in combination with the original evaporator temperature from Step 1 and repeat Steps 2 to 5 as necessary to determine the condenser capacity at which the system balances. Points *A* and *B* on Fig. 5 represent the results of these calculations. Two points will normally be sufficient to determine the balancing Q_c.

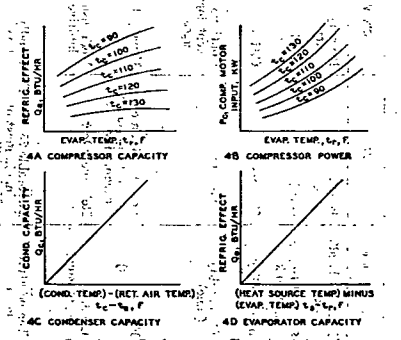


Fig. 4 .... Performance Characteristics of Heat-Pump Components

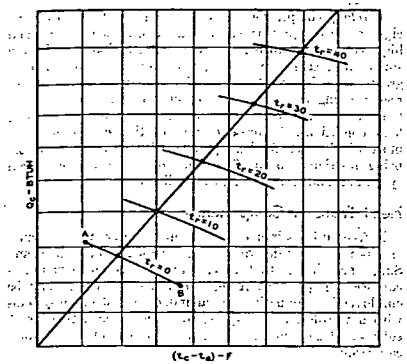


Fig. 5 .... Heat-Pump System Balance

7. Select other evaporator temperatures and repeat Steps 1-6 (See Fig. 5.)
8. For each evaporator temperature, find the corresponding heat source temperature t_a from chart similar to *D* of Fig. 4.
9. Make allowance for pumps or fans required for moving the fluids that pick up heat from the heat source and carry it away to the heat sink. For example, for an air-to-air heat pump having one motor and fan within the indoor-air stream and another motor and fan within the outdoor-air stream, the following factors must be considered:

a. The entire electrical input to both motors must be added to the compressor motor power in order to get the total heat pump input.

b. The entire indoor fan motor input, expressed in heat units, affects the heat pump net capacity by adding to the indoor coil capacity in heating, and by subtracting from the indoor coil capacity in cooling.

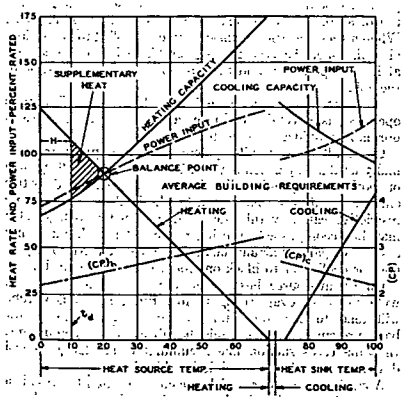


Fig. 6 .... Operating Characteristics of Single-Stage Unmodulated Heat Pump

c. The entire input of the outdoor fan motor is rejected to the outdoor-air stream and has no direct affect on the heating or cooling capacity of the heat pump.

d. When a fan and motor are upstream of the evaporator or condenser, the air enters the heat exchanger at a warmer temperature than otherwise, and a correction is required in constructing diagrams such as *C* and *D* of Fig. 4. If the fan and motor are downstream, no such correction is needed.

With the conditions of system balance found in the foregoing procedure, it is a relatively simple matter to establish the heating performance characteristics. The net heating effect may consist only of the condenser heat, or, depending upon the system design, may also include heat losses from the compressor and motors, and the heating effect of a refrigerant subcooler coil.

The cooling performance can be determined in a similar manner.

For a heat pump which employs a constant temperature heat source, a few computations will generally establish the balancing conditions for t_e and t_c. For a heat pump having source temperature subject to considerable variation (e.g. air source), the balancing conditions for a wide range of t_e will be necessary.

Fig. 6 shows the performance characteristics of a typical heat pump determined either from actual system tests or from an analytical procedure such as already described. Also shown are the heating and cooling loads for a typical building. The temperature at which the heat-pump capacity and the building heat requirement are equal is referred to as the *balance point*. If the balance point is above the heating design temperature t_d, supplemental heat will be required as denoted by the shaded area. Capacity, power input, and coefficient of performance characteristics can vary appreciably with equipment size and design. In residential sizes, a coefficient of performance of approximately 2 may apply under typical cooling and heating operating conditions.[41] Specification data published[42] for several hundred air-to-air heat pump models having cooling capacities from 20,000 to 150,000 Btuh and higher show coefficients of performance in cooling that are typically within the range of from 1.8 to 2.8 at rating conditions of 80 F dry-bulb, 67 F wet-bulb indoors, and 95 F outdoors. Generally, the larger sizes have higher coefficients of performance.

HEAT-PUMP COMPONENTS

For the most part, the components used in heat pumps and the practices followed bear a direct relation to the low temperature refrigeration art. This section will outline the major components used and point out characteristics or special considerations which apply to the heat-pump field.

Compressors

Reciprocating compressors are used more than any other type on systems in the general range of ½ to 100 tons, and larger. A brief description of this type of compessor is given in Chapter 38. For the most economical application, it is general practice to select the reciprocating compressor to provide the desired cooling capacity. The cooling capacity is the evaporator capacity and represents the ability of the compressor to pump refrigerant vapor between the existing temperature limits. When heating, the capacity of a particular compressor is the sum of the evaporator capacity (i.e., heat-source coil capacity) and the heat equivalent of the compressor work.

A compressor normally employed for comfort cooling use will have a clearance volume (ratio of gas volume remaining in cylinder after compression stroke to total swept-cylinder