quently suitable for defrost relief from evaporator to suction pressure, as large capacity relief from a pressure vessel to the low side, or as a liquid refrigerant pump relief from pump discharge to the accumulator to prevent excessive pump pressures when some evaporators are valved closed.

PART III: CAPILLARY TUBES

All refrigerating units require a pressure-reducing device to meter the flow of refrigerant to the low side in accordance with the demands placed on the system. With the advent of the hermetic compressor and the halocarbon refrigerants the capillary tube became practicable and rapidly achieved popularity, especially with the smaller unitary hermetic equipment, such as household refrigerators and freezers, dehumidifiers, and room air conditioners. More recently, it has been extended to larger units such as unitary air conditioners in sizes up to 10 tons capacity.

The capillary operates on the principle that liquid passes through it much more readily than gas. It consists of a small diameter line, which, when used for the purpose of controlling the flow of refrigerant in a system, connects the outlet of the condenser to the inlet of the evaporator. It is sometimes soldered to the outer surface of the suction line for heat exchange purposes.

A high-side liquid receiver is not normally used with a capillary, and a corresponding reduction in refrigerant charge could result. In a few instances, such as with household refrigerators and freezers, it is customary to employ a small low side accumulator. The pressure equalizing characteristic of a capillary makes possible the use of a low starting torque motor compressor. Inherently, a capillary does not operate as efficiently over a wide range of conditions as does a thermostatic expansion valve, but due to counterbalancing factors in most applications, its performance is generally very good. The simplicity of the capillary gives it the advantage of greatly reduced cost.

Theory

As has been indicated, it is the characteristic of the capillary to pass liquid much more readily than gas that makes it a practical metering device. Let it be assumed that a condenser-to-evaporator capillary has been sized to permit the desired flow of refrigerant with a liquid seal at its inlet. If a system unbalance occurs so that some gas (uncondensed refrigerant) enters the capillary, this gas will tend to considerably reduce the mass flow of refrigerant with little or no change in the system pressures. If the opposite type of unbalance occurs, liquid refrigerant will back up in the condenser. This condition will tend to cause subcooling and increase the mass flow of refrigerant. If properly sized for the application, the capillary thus tends to automatically compensate for load and system variations and will give acceptable performance over a wide range of operating conditions.

A common flow condition involves subcooled liquid at the entrance to the capillary. Bolstad[1] demonstrates the flow behavior from temperature and pressure measurements along the tube:

"With subcooled liquid entering the capillary tube, the pressure distribution along the tube is similar to that shown in Fig. 32. At the entrance to the tube, section 0-1, there is slight pressure drop which was usually unreadable on the gages. From point 1 to point 2, the pressure drop is linear. In the portion of the tube 0-1-2, the refrigerant is entirely in the liquid state, and at point 2, the first bubble of vapor forms. From point 2 to the end of the tube, the pressure drop is not linear, the pressure drop per unit length increasing as the end of the tube is approached. For this portion of the tube, both the saturated liquid and saturated vapor phases are present, the percent and volume of vapor increasing in the direction of flow.

In most of the runs there was observed a significant pressure drop from the end of the tube into the evaporator space.

With a saturation temperature scale corresponding to the pressure scale superimposed along the vertical axis, it is possible to plot the observed temperatures in a more meaningful way than if a uniform temperature scale were used. The temperature is constant for the first portion of the tube 0-1-2. At point 2, the pressure has dropped to the saturation pressure corresponding to this temperature. Further pressure drop beyond point 2 is accompanied by a corresponding drop in temperature, the temperature being the saturation temperature corresponding to the pressure. As a consequence, the pressure and temperature lines coincide from point 2 to the end of the tube."

The rate of refrigerant flow through a capillary always increases with an increase in inlet pressure. It also increases with a decrease in external outlet pressure down to a certain *critical* value, below which the flow does not change. Fig. 32 illustrates a case where the outlet pressure inside the capillary has reached the critical value, which happens to be higher than the external pressure. Point 2 in Fig. 32, where the first gas bubble appears, is called the *bubble point*. The preceding portion of capillary is called the *liquid length*, and that following is called the *two-phase* length.

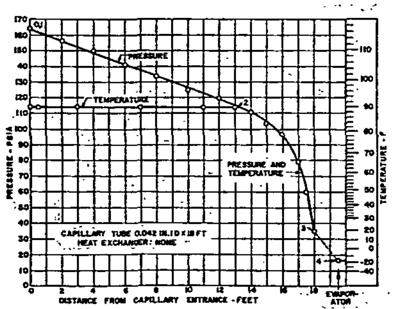


Fig. 32 .... Pressure and Temperature Distribution Along Typical Capillary Tube

System Design Factors

The high side must be carefully designed for use with a capillary. If liquid backs up in the condenser, enough refrigerant may be removed from the evaporator to cause an undercharged condition. This can be improved by decreasing the high-side volume so that less liquid refrigerant will be required to increase the discharge pressure to achieve balanced conditions. The total volume of the high side usually represents a compromise, since it may be necessary to also provide sufficient refrigerant storage volume to protect against excessive discharge pressures during high load conditions. The high-side volume should be sufficient to contain the entire refrigerant charge to prevent hydrostatic rupture failure in case of capillary stoppage.

Another consideration in high-side design, where cyclic operation is involved, is that of unloading during the off period. When unit operation ceases, the capillary continues to pass refrigerant from the high side to the low side until pressures are equalized. Care must be taken to provide good drainage of the liquid into the capillary during this unloading interval. If liquid is trapped in the high side, it will evaporate there during the off cycle. It will then pass to the low side as a warm gas, where it condenses and adds latent heat to the evaporator. Liquid trapping may also increase the time required for the pressures to equalize after the compressor stops operating. If this interval is too long, the compressor may not be sufficiently unloaded at cut-in to permit easy starting.

The important design parameters in low-side design are total refrigerant charge and charge tolerance. For many reasons the total refrigerant charge should be held to a minimum consistent with satisfactory performance. However, a high tolerance may be necessary to minimize the effect of a varying distribution of refrigerant in the system during operation. A good low-side design will achieve both objectives.

The amount of refrigerant in the evaporator is at its maximum during the off cycle and at its minimum value during the running cycle. The suction piping should be arranged to reduce to a minimum the adverse effects of the variable charge distribution. A suitable liquid accumulator is sometimes necessary.

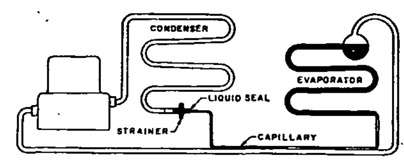
When a suction line heat exchanger is used, the excess capillary may be coiled and located at either end of the exchanger. Although more efficient heat exchange may be obtained if the excess capillary is coiled at the evaporator, experience has shown that system stability is enhanced if a portion of the capillary is located at the condenser. Care should, of course, be exercised in forming the bends and coils to avoid local restrictions.

In general, one should not locate all of the capillary at the evaporator and precede it with a conventional large bore liquid line in heat exchange with the suction line. With this particular arrangement, an overcharge into the suction line places the low side and high side in heat exchange relationship in the heat exchanger and will result in serious instability. The increased cooling of the refrigerant entering the capillary, due to the liquid in the suction line, increases the capillary capacity and reduces the liquid stored in the condenser.

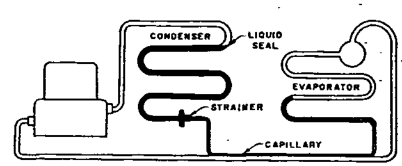
Capacity Balance Characteristic

The selection of a capillary tube will depend on the application and the anticipated range of operating conditions. One approach to the problem involves the concept of *capacity balance*. A refrigerating system may be said to be operating at the condition of capacity balance when the resistance of the capillary is sufficient to maintain a liquid seal at its entrance without excess liquid accumulating in the high side of the system. (See Fig. 33.) Only one such *capacity balance point* exists for any given compressor discharge pressure. A curve through the capacity balance points for a range of compressor discharge pressures is called the *capacity balance characteristic* of the system. Such a curve is shown in Fig. 34. Ambient temperatures are drawn on the chart for a typical air-cooled system. A given set of compressor discharge and suction pressures are associated with fixed condenser and evaporator pressure drops; therefore they establish the capillary inlet and outlet pressures.

The capacity balance characteristic curve for any combination of a compressor and capillary may be determined experimentally by means of the arrangement shown in Fig. 35, which makes it possible to independently vary the suction and discharge pressures until capacity balance is obtained.



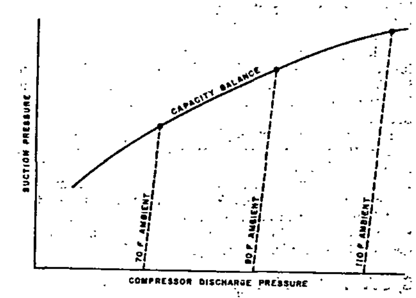
[a] *Capillary selected for capacity balance conditions. Liquid seal at capillary inlet but no excess liquid in condenser. Compressor discharge and suction pressures normal. Evaporator properly charged.*



[b] *Too much capillary resistance—liquid refrigerant backs up in condenser and causes evaporator to be undercharged. Compressor discharge pressure may be abnormally high. Suction pressure below normal. Bottom of condenser subcooled.*

Fig. 33 ... : Effect of Capillary Tube Selection on Refrigerant Distribution[a,b]

The desired suction pressure may be obtained by regulating the heat input to the low side, usually by means of electric heaters; the desired discharge pressure may be obtained by means of a suitable controlled water-cooled condenser. A liquid indicator is located at the entrance to the capillary. The usual test procedure is to hold the high-side pressure constant and, with gas bubbling through the sight glass, slowly increase the suction pressure until a liquid seal forms at the capillary entrance. Repeating this procedure at various discharge pressures will readily determine the capacity balance characteristic curve similar to that shown in Fig. 34. This equipment may



[a] *Operation below this curve results in a mixture of liquid and vapor entering the capillary. Operation above the capacity balance points causes liquid to back up in the condenser and elevate its pressure.*

Fig 34 .... The Capacity Balance Characteristic of a Capillary System[a]