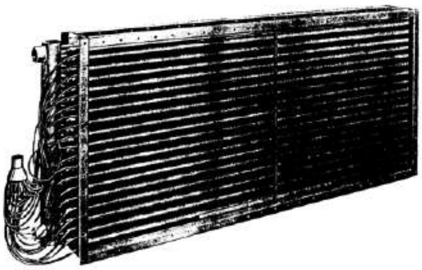
Chapter Three

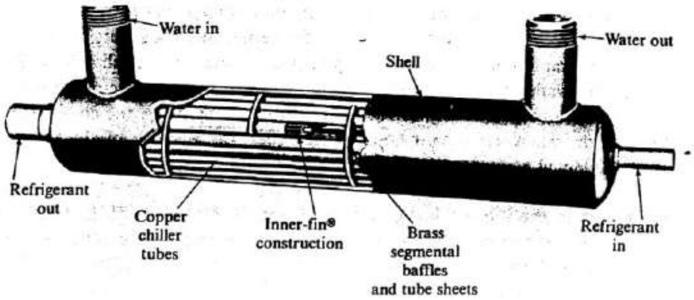
Evaporators: Heat Transfer and Fluid Flows Approach

1. Introduction

- In most refrigerating evaporators, the refrigerant boils in the tubes and cools the fluid that passes over the outside of the tubes. Evaporators that boil refrigerant in the tubes are often called *direct-expansion evaporators.*
- The tubes in the liquid chiller have fins inside the tubes in order to increase the conductance on the refrigerant side.



Air-cooling evaporator



A liquid chilling evaporator in which refrigerant boils inside finned tubes

- Direct-expansion evaporators used for air-conditioning applications are usually fed by an expansion valve that regulates the flow of liquid so that the refrigerant vapor leaves the evaporator with some superheat
- Another concept is the liquid-recirculation or liquid-overfeed evaporator in Figure below, in which excess liquid at low pressure and temperature is pumped to the evaporator. Some liquid boils in the evaporator, and the remainder floods out of the outlet. The liquid from the evaporator is separated out, and the vapor flows on to the compressor. Low-temperature industrial - refrigeration systems often use this type of evaporator, which has the advantage of wetting all the interior surfaces of the evaporator and maintaining a high coefficient of heat transfer.

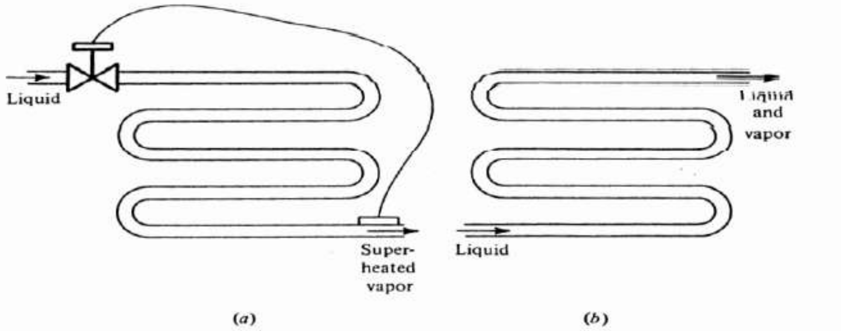


Figure 12-19 *(a)* Air-conditioning evaporator with refrigerant leaving in a superheated state, *(b)* liquid-recirculation evaporator with liquid refrigerant carried out of the evaporator.

- While refrigerant boils inside the tubes of most commercial evaporators, in one important class of liquid-chilling evaporator the refrigerant boils outside the tubes. This type of evaporator is standard in centrifugal-compressor applications. Sometimes such an evaporator is used in conjunction with reciprocating compressors, but in such applications provision must be made for returning oil to the compressor. In the evaporators where refrigerant boils in the tubes, the velocity of the refrigerant vapor is maintained high enough to carry oil back to the compressor.

2. Boiling in the shell

- It is difficult to predict the boiling coefficient accurately because of the complexities of the mechanisms. Furthermore, the coefficients follow some different rules when the boiling takes place in the shell outside the tubes, in contrast to boiling inside the tubes. Some trends that usually occur will be presented in this and the next section

- The classic prediction for the heat-transfer coefficient for pool boiling of water at atmospheric pressure is shown in Fig. 12-20. The tests were conducted by immersing a heated wire in a container of water. In the boiling regime *AB* the boiling is called *nucleate boiling*, where bubbles form on the surface and rise through the pool. The equation of the curve is approximately

$$\frac{q}{A} = C\,\Delta t^{3\text{ to }4}$$

where q = rate of heat transfer, W
A = heat-transfer area, m^2
C = constant
Δt = difference in temperature between metal surface and boiling fluid, K

To write the equation in another form divide both sides by Δt,

$$\frac{q}{A\ \Delta t} = h_r = C\ \Delta t^{2\text{ to }3}$$

where h_r is the boiling coefficient, $W/(m^2 \cdot K)$. The value of h_r increases as the temperature difference increases, which physically is due to the greater agitation. The disturbance frees the bubbles of vapor from the metal surface sooner and allows the liquid to come into contact with the metal.

The rate of evaporation can increase to a peak, point B, where so much vapor covers the metal surface that the liquid can no longer intimately contact the metal. A further increase in the temperature difference decreases the rate of heat transfer.

The graph in Fig. 12-20 is useful in predicting the trends for heat-transfer coefficients for boiling outside tube bundles. Hoffmann[14] summarized the work of several investigators to provide the band shown in Fig. 12-21.

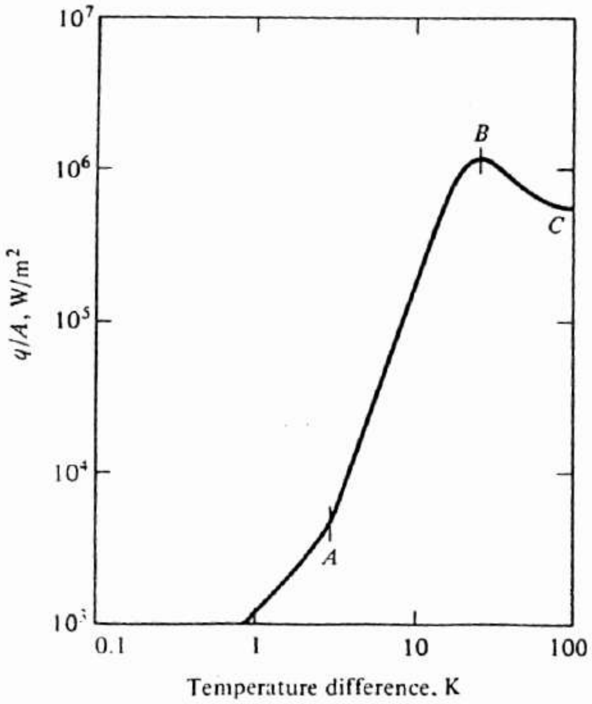


Figure 12-20 Heat-transfer coefficient for pool boiling of water. *(From W. H. McAdams, "Heat Transmission," 3d ed., p. 370, McGraw-Hill, New York, 1954.)*

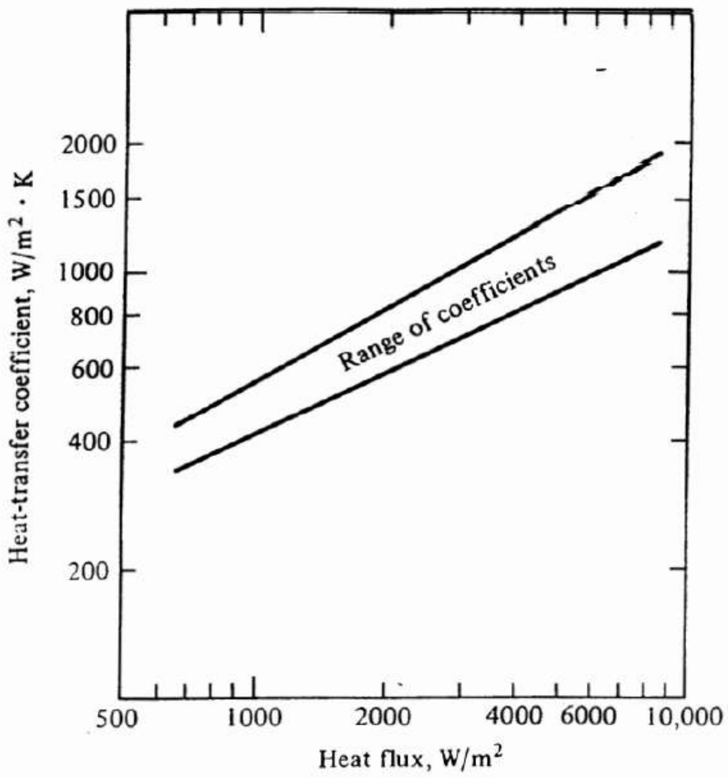


Figure 12-21 Heat-transfer coefficients for refrigerants 12 and 22 boiling outside of tube bundles.

Boiling inside tubes

- When refrigerant boils inside the tubes, the heat-transfer coefficient changes progressively as the refrigerant flows through the tube. The refrigerant enters the evaporator tube with a low fraction of vapor. As the refrigerant proceeds through the tube, the fraction of vapor increases, intensifying the agitation and increasing the heat-transfer coefficient. When the refrigerant is nearly all vaporized, the coefficient drops off to the magnitude applicable to vapor transferring heat by forced convection.
- Figure 12-22 shows local coefficients throughout a tube for three different levels of temperature. The heat-transfer coefficient is highest for the high evaporating temperature, probably because at high evaporating temperatures and pressures the vapor density is high, permitting a greater fraction of the metal to be wetted with liquid

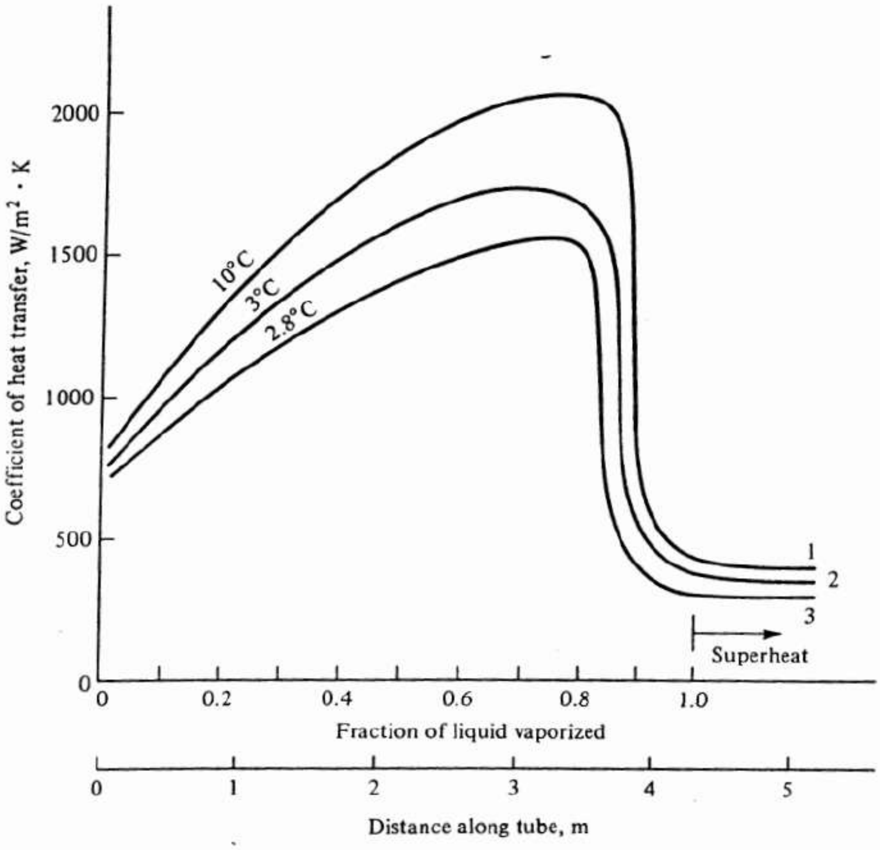
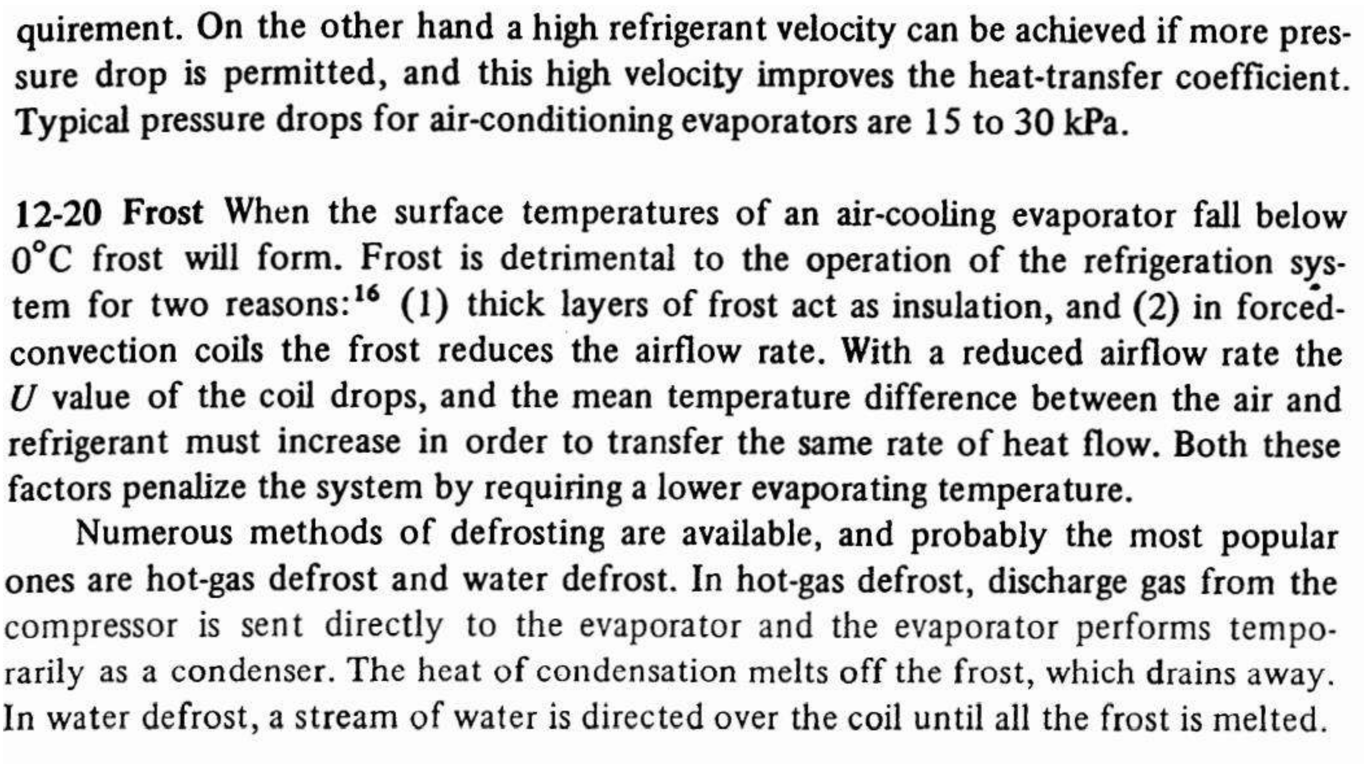


Figure 12-22 Heat-transfer coefficients of refrigerant 22 boiling inside tubes. Curve 1 at 10°C, curve 2 at 3°C, and curve 3 at 2.8°C temperatures of evaporation.[15]

12-18 Evaporator performance From the discussion of boiling heat-transfer coefficients in Secs. 12-16 and 12-17 the coefficient will be expected to increase with an increase in loading. This assumption is borne out by the performance of commercial evaporators. We encounter the performance of evaporators again in Chap.14, and Fig. 14-8 shows the performance of a water-chilling evaporator where the refrigerant boils inside the tubes. For a given temperature of entering water the lines on the capacity-versus-evaporating-temperature graph would be straight if the *U* value remained constant. Instead, the lines are curved upward, indicating an increase in *U* value at more intense loadings due to the improved boiling heat-transfer coefficient.

12-19 Pressure drop in tubes The pressure of the refrigerant drops as it flows through tube-type evaporators. The effect of pressure drop on system performance is that the compressor must pump from a lower suction pressure, which increases the power re-



quirement. On the other hand a high refrigerant velocity can be achieved if more pressure drop is permitted, and this high velocity improves the heat-transfer coefficient. Typical pressure drops for air-conditioning evaporators are 15 to 30 kPa.

12-20 Frost When the surface temperatures of an air-cooling evaporator fall below 0°C frost will form. Frost is detrimental to the operation of the refrigeration system for two reasons:[16] (1) thick layers of frost act as insulation, and (2) in forced-convection coils the frost reduces the airflow rate. With a reduced airflow rate the *U* value of the coil drops, and the mean temperature difference between the air and refrigerant must increase in order to transfer the same rate of heat flow. Both these factors penalize the system by requiring a lower evaporating temperature.

Numerous methods of defrosting are available, and probably the most popular ones are hot-gas defrost and water defrost. In hot-gas defrost, discharge gas from the compressor is sent directly to the evaporator and the evaporator performs temporarily as a condenser. The heat of condensation melts off the frost, which drains away. In water defrost, a stream of water is directed over the coil until all the frost is melted.

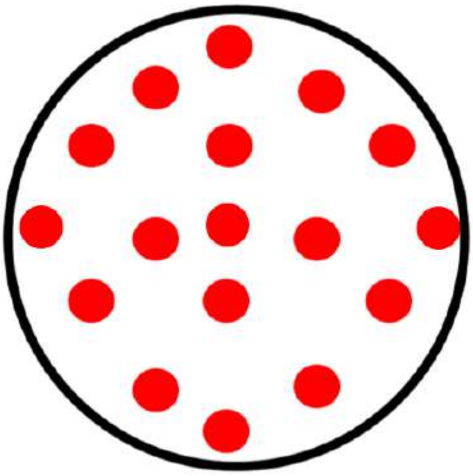
Problems on Refrigeration Systems

Problem. 1: Calculate the mean condensing heat-transfer coefficient when refrigerant R-12 condenses on the outside of the horizontal tubes in a shell-and-tube condenser. The outside diameter of the tubes is 19 mm, and in the vertical rows of tubes there are respectively, two, three, four, three, and two tubes. The refrigerant is condensing at a temperature of 52 C and the temperature of the tubes is 44 C.

Problem. 2: An air-cooled condenser is to reject 75 kJ/s of heat from a condensing refrigerant to air. The condenser has an air-side area of 200 m^2 and a U value based on this area is 40 $W/m^2.K$; it is supplied with 5 m^3/s of air, which has a density of 1.15 kg/m^3 and its specific heat at constant pressure is 1000 J/kg.K If the condensing temperature is to be limited to 50 °C, Determine;

1. **LMTD**
2. **Inlet and exit temperature of air**

Problem. 3: Determine the mean condensing heat-transfer coefficient when refrigerant R – 22 condenses on the outside of the horizontal tubes in a water – cooled condenser. The outside diameter of the tubes is 15 mm. The refrigerant is condensing at a temperature of 50 °C and the temperature of the tubes is 42 °C.



Problem. 4: **Water – cooled condenser used a refrigerant R-22 flows over the tubes while the water flows inside the tube. The refrigerating system provides a capacity of 70 kW for air conditioning. The evaporating temperature is 10°C, and the condensing temperature is 50°C at design conditions. Water from a cooling tower enters the condenser at 28°C and leaves at 35°C. Consider the compressor is hermetically sealed. A two – pass condenser with 28 tubes, arranged as shown below in the figure inserted below. The tubes are made of copper with its thermal conductivity is (380 W/m.K), 12 mm ID and 14 mm OD.**

Determine, step by step and in – full details each of the following points;

I. **Rate of transfer that rejected at the condenser in watts units.**

II. **Mean condensation coefficient for vapor condensing on the outside of horizontal tube.**

III. **Reynolds Number, Prandlt Number, Nusselt Number for water flows inside the pipe.**

IV. **Water – side heat transfer coefficient.**

V. **The overall heat transfer coefficient.**

VI. **LMTD**

Take the thermophysical properties of water;

$\mu = 0.000773\ Pa.s \quad \rho = 1\ kg/\text{Liter} \quad k = 0.619\ W/m.K \quad C_p = 4200\ j/kg.K$