Refrigeration Systems

Based Upon the Basic Principles of Thermodynamics, Heat Transfer and Fluid Flows

Air Conditioning and Refrigeration Techniques Engineering Department
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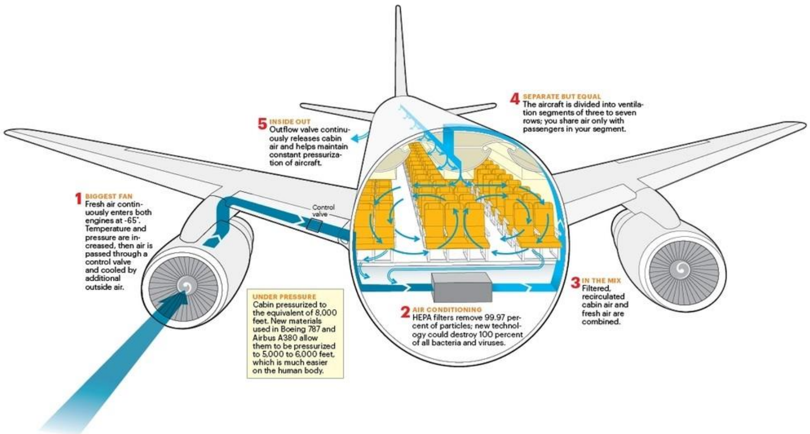

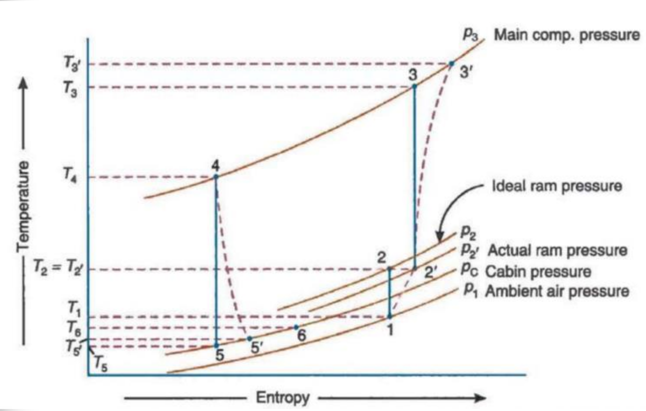

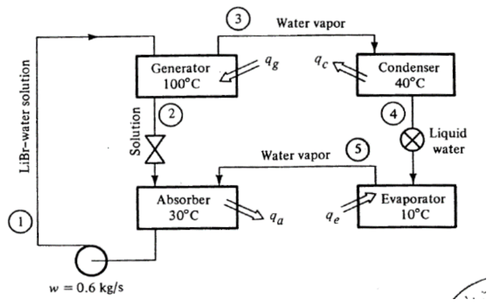

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INTRODUCTION

Basic Principles of Refrigeration

- If you were to place a hot cup of coffee on a table and leave it for a while, the heat in the coffee would be transferred to the materials in contact with the coffee, i.e. the cup, the table and the surrounding air.
- As the heat is transferred, the coffee in time cools. Using the same principle, refrigeration works by removing heat from a product and transferring that heat to the outside air.

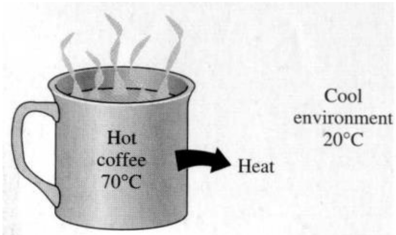


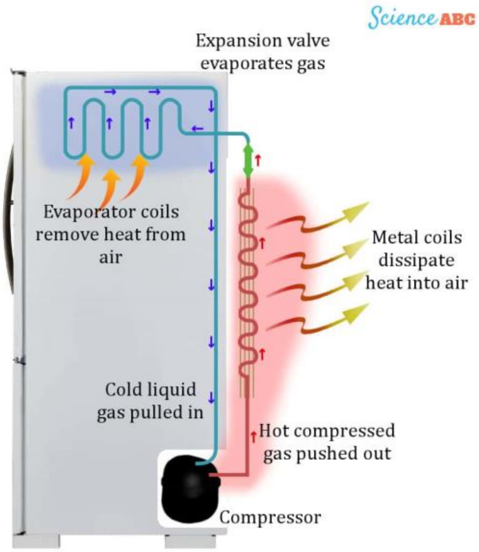
FIGURE 1–3
Heat flows in the direction of decreasing temperature.

There are **five** basic components of a refrigeration system, these are:

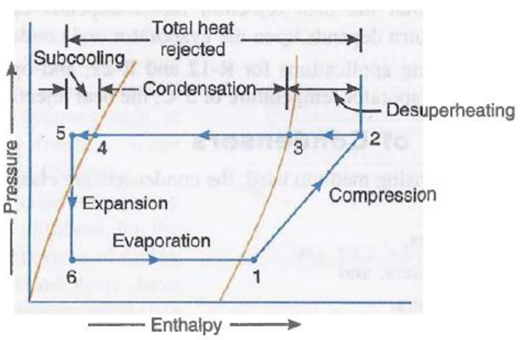
1. Evaporator
2. Compressor
3. Condenser
4. Expansion Valve
5. Refrigerant; to conduct the heat from the product.

When liquid evaporates it absorbs heat

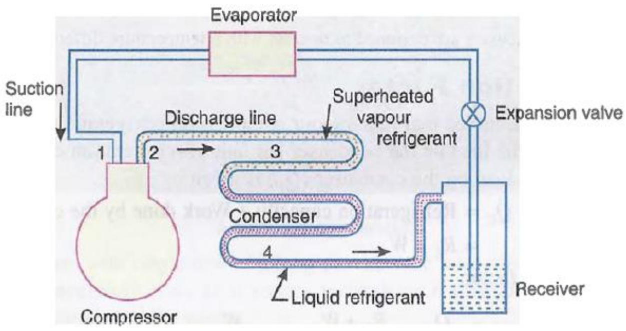
When liquid condenses it releases heat



- In order for refrigeration cycle to operate successfully each component must be present within the refrigeration system.



(*b*) *p-h* diagram of a simple refrigerating system.



(*a*) Schematic diagram of a simple refrigerating system.

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Chapter One: Condensers and Evaporators

1.1. Condensers and evaporators as heat exchangers

- Since both the condenser and evaporator are heat exchangers, they have certain features in common. One classification of condensers and evaporators (Table 1.1) is according to whether the refrigerant is on the inside or outside of the tubes and whether the fluid cooling the condenser or being refrigerated is a gas or a liquid. The gas referred to in Table 1.1 is usually air, and the liquid is usually water, but other substances are used as well.

Component	Refrigerant	Fluid
Condenser	Inside tubes	Gas outside Liquid outside†
	Outside tubes	Gas inside† Liquid inside
Evaporator	Inside tubes	Gas outside Liquid outside
	Outside tubes	Gas inside† Liquid inside

- The most widely used types of condensers and evaporators are shell-and-tube heat exchangers (Fig. 1) and finned-coil heat exchangers (Fig. 2).

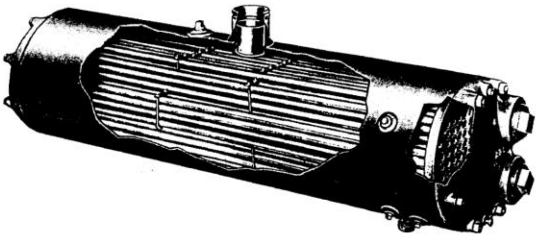

Fig. 1. Shell-and-tube heat exchangers

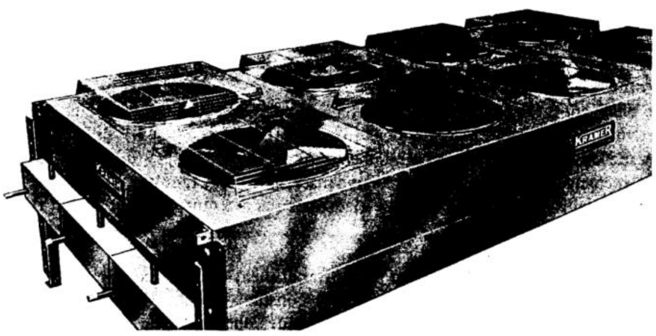

Fig. 2. Finned-coil heat exchangers

1.2. Overall heat-transfer coefficient

The overall heat-transfer coefficient, for an evaporator or condenser is the proportionality constant, when multiplied by the heat-transfer area and the mean temperature difference between the fluids, yields the rate of heat transfer

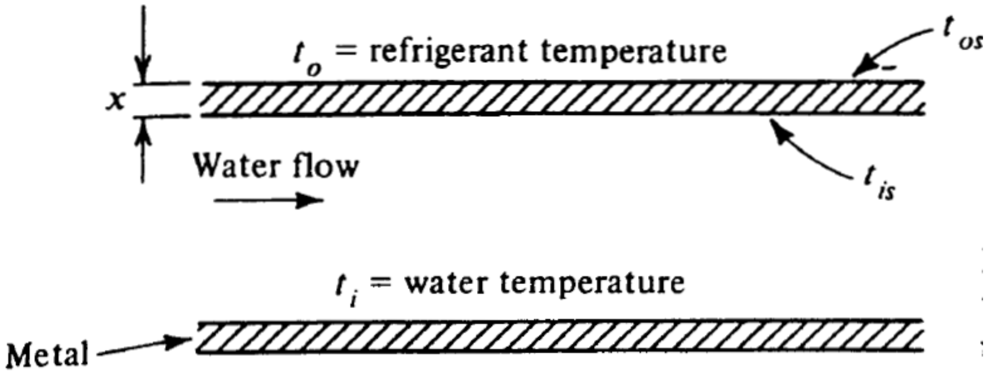

Fig. 3. Heat transfer between refrigerant and water through a tube

If heat flows across a tube, as in Fig. 3, between refrigerant on the outside and water on the inside, for example, under steady-state conditions the rate of heat transfer q in watts is the same from the refrigerant to the outside surface of the tube, from the outside to the inside surface of the tube, and from the inside surface of the tube to the water. The expressions for q in each of these transfers are, respectively,

$$q = h_o A_o (t_o - t_{os}) \quad (1\text{-}1)$$

$$q = \frac{k}{x} A_m (t_{os} - t_{is}) \quad (1\text{-}2)$$

$$q = h_i A_i (t_{is} - t_i) \quad (1\text{-}3)$$

q = rate of heat transfer, W
h_o = heat-transfer coefficient on outside of tube, $W/m^2 \cdot K$
A_o = outside area of tube, m^2
t_o = refrigerant temperature, °C
t_{os} = temperature of outside surface of tube, °C
k = conductivity of tube metal, $W/m \cdot K$
x = thickness of tube, m
t_{is} = temperature of inside surface of tube, °C
A_m = mean circumferential area of tube, m^2
h_i = heat-transfer coefficient on inside of tube, $W/m^2 \cdot K$
A_i = inside area of tube, m^2
t_i = water temperature, °C

To express the overall heat-transfer coefficient the area on which the coefficient is based must be specified. Two acceptable expressions for the overall heat-transfer coefficient are

$$q = U_o A_o (t_o - t_i) \quad (1\text{-}4)$$

$$q = U_i A_i (t_o - t_i) \quad (1\text{-}5)$$

$$q = U_o A_o (t_o - t_i) \quad (1\text{-}4)$$

and

$$q = U_i A_i (t_o - t_i) \quad (1\text{-}5)$$

where U_o = overall heat-transfer coefficient based on outside area, $W/m^2 \cdot K$
U_i = overall heat-transfer coefficient based on inside area, $W/m^2 \cdot K$

From Eqs. (1-4) and (1-5) it is clear that $U_o A_o = U_i A_i$. The U value is always associated with an area. Knowledge of U_o or U_i facilitates computation of the rate of heat transfer q.

To compute the U value from knowledge of the individual heat-transfer coefficients, first divide Eq. (1-1) by $h_o A_o$, Eq. (1-2) by kA_m/x, and Eq. (1-3) by $h_i A_i$, leaving only the temperature differences on the right sides of the equations. Next add the three equations, giving

$$\frac{q}{h_o A_o} + \frac{qx}{kA_m} + \frac{q}{h_i A_i} = (t_o - t_{os}) + (t_{os} - t_{is}) + (t_{is} - t_i) = t_o - t_i \quad (1\text{-}6)$$

Alternate expressions for $t_0 - t_i$; are available from Eqs. *4 – 5*

$$t_o - t_i = \frac{q}{U_o A_o} = \frac{q}{U_i A_i} \quad (1\text{-}7)$$

Equating Eqs. (1-6) and (1-7) and canceling q provides an expression for computing the U values

$$\frac{1}{U_o A_o} = \frac{1}{U_i A_i} = \frac{1}{h_o A_o} + \frac{x}{kA_m} + \frac{1}{h_i A_i} \quad (1\text{-}8)$$

The physical interpretation of the terms in Eq. (1-8) is that $1/U_o A_o$ and $1/U_i A_i$ are the total resistances to heat transfer between the refrigerant and water. This total resistance is the sum of the individual resistances

1. From the refrigerant to the outside surface of the tube $1/h_o A_o$
2. Through the tube $x/(kA_m)$
3. From the inside surface of the tube to the water $1/h_i A_i$

1.3. Liquid in tubes; heat transfer and pressure drop

1.3.1. Heat Transfer

The expression for the heat transfer coefficient for fluids flowing inside tubes

$$\text{Reynolds number Re} = \frac{\rho V D}{\mu}$$

$$\text{Prandtl number Pr} = \frac{\mu c_p}{k}$$

$$\text{Nusselt number Nu} = \frac{h_c D}{k}$$

$$\text{Nu} = C\,\text{Re}^n\,\text{Pr}^m$$

where n and m are exponents. The constant C and exponents in the equation are

$$\frac{hD}{k} = 0.023\left(\frac{VD\rho}{\mu}\right)^{0.8}\left(\frac{c_p\mu}{k}\right)^{0.4} \qquad 1.9$$

where h = convection coefficient, $W/m^2 \cdot K$
D = ID of tube, m
k = thermal conductivity of fluid, $W/m \cdot K$
V = mean velocity of fluid, m/s
ρ = density of fluid, kg/m^3
μ = viscosity of fluid, $Pa \cdot s$
c_p = specific heat of fluid, $J/kg \cdot K$

Problem. 1: Compute the heat-transfer coefficient for water flow inside the tubes (8 mm ID) of an evaporator if the water temperature is 10°C and its velocity is 2 m/s.

Solution The properties of water at 10°C are

μ = 0.00131 Pa · s ρ = 1000 kg/m^3 k = 0.573 W/m · K c_p = 4190 J/kg · K

The Reynolds number is

$$Re = \frac{(2\ m/s)(0.008\ m)(1000\ kg/m^3)}{0.00131\ Pa \cdot s} = 12{,}214$$

This value of the Reynolds number indicates that the flow is turbulent, so Eq. (12-9) applies. The Prandtl number is

$$Pr = \frac{(4190\ J/kg \cdot K)(0.00131\ Pa \cdot s)}{0.573\ W/m \cdot K} = 9.6$$

The Nusselt number can now be computed from Eq. (12-9)

$$Nu = 0.023(12{,}214^{0.8})(9.6^{0.4}) = 106$$

from which the heat-transfer coefficient can be computed as

$$h = \frac{0.573\ W/m \cdot K}{0.008\ m}(106) = 7592\ W/m^2 \cdot K$$

Problem. 2: A refrigerant 22 condenser has four water passes and a total of 60 copper tubes that are 14 mm ID and have 2 mm wall thickness. The conductivity of copper is 390 W/m.K. The outside of the tubes is finned so that the ratio of outside to inside area is 1.7. The cooling-water flow through the condenser tubes is 3.8 L/s.

(a) Calculate the water-side coefficient if the water us at an average temperature of 30 C, at which temperature k = 0.614 W/m.K, ρ = 996 kg/m3, and m = 0.000803 Pa.s.
(b) Using a mean condensing coefficient of 1420 W/m2.K, calculate the overall heat-transfer coefficient based on the condensing area.

(a) Water-side coefficient:
Eq. 12-19.

$$\frac{hD}{k} = 0.023\left(\frac{VD\rho}{\mu}\right)^{0.8}\left(\frac{c_p\mu}{k}\right)^{0.4}$$

D = 14 mm = 0.014 m
k = 0.614 W/m.K
ρ = 996 kg/m^3
μ = 0.000803 Pa.s
c_p = 4190 J/kg.K

$$V = \frac{3.8\times10^{-3}\ m^3/s}{\left(\frac{60}{4}\right)\left(\frac{\pi}{4}\right)(0.014\ m)^2}$$

V = 1.6457 m/s

$$\frac{h(0.014)}{0.614} = 0.023\left(\frac{(1.6457)(0.014)(996)}{0.000803}\right)^{0.8}\left(\frac{(4190)(0.00803)}{0.614}\right)^{0.4}$$

h = 7,313 W/m^2.K - - - Ans.

(b) Overall heat-transfer coefficient.
Eq. 12-8.

$$\frac{1}{U_oA_o} = \frac{1}{h_oA_o} + \frac{x}{kA_m} + \frac{1}{h_iA_i}$$

$$\frac{1}{U_o} = \frac{1}{h_o} + \frac{xA_o}{kA_m} + \frac{A_o}{h_iA_i}$$

h_o = 1420 W/m^2.K
k = 390 W/m.K
A_o / A_i = 1.7

$$A_m = \tfrac{1}{2}(A_o + A_i)$$

$$A_m = \tfrac{1}{2}\left(A_o + \frac{A_o}{1.7}\right)$$

A_o / A_m = 1.25926
x = 2 mm = 0.002 m
h_i = 7,313 W/m^2.K

$$\frac{1}{U_o} = \frac{1}{1420} + \frac{(0.002)(1.2596)}{390} + \frac{1.7}{7313}$$

U_o = 1060 W/m^2.K - - - Ans.