ME 418
Lecture 14 - Vapor Compression Equipment – II
In-Class Notes for Fall 2024

- Expansion devices
- Evaporator
- Condenser
- System integration
- Heat pumps

Expansion Devices

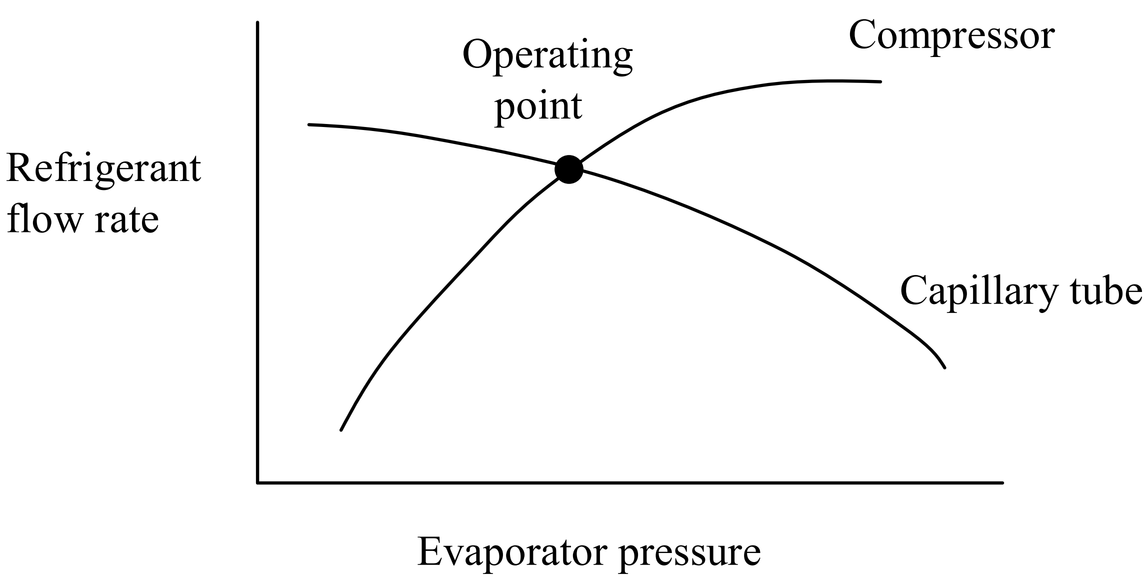
Uncontrollable devices:

- Fixed orifice
- Capillary tube

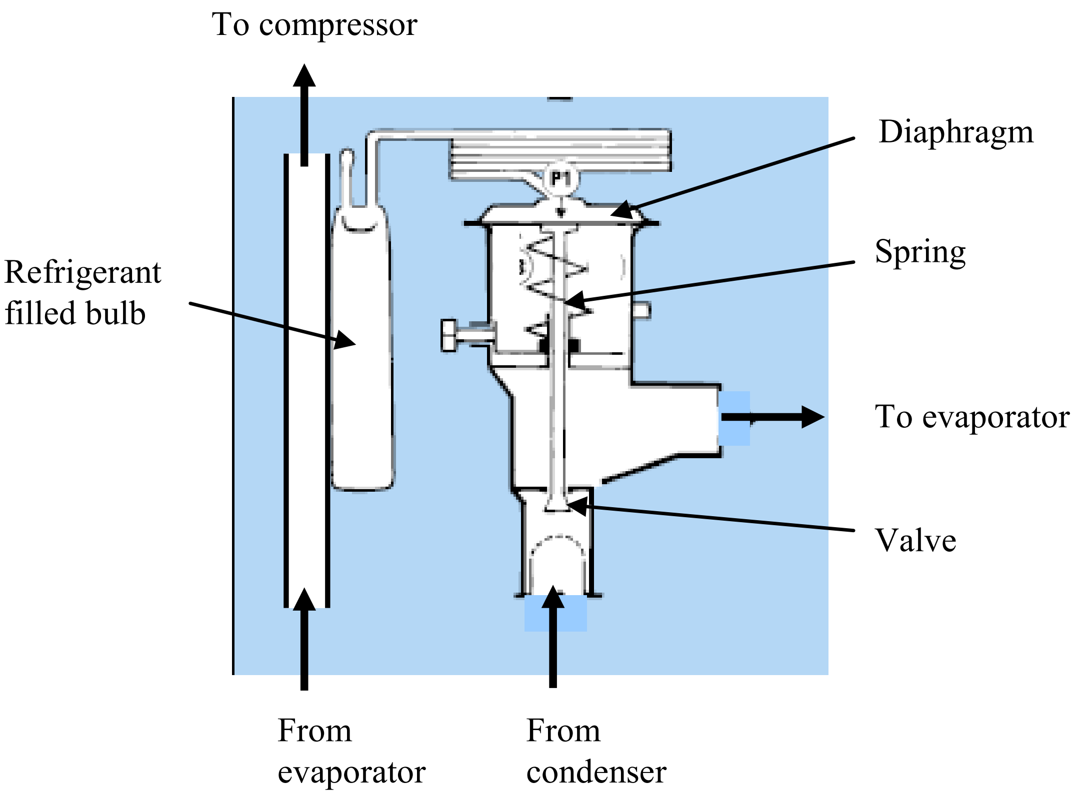
Controllable devices:

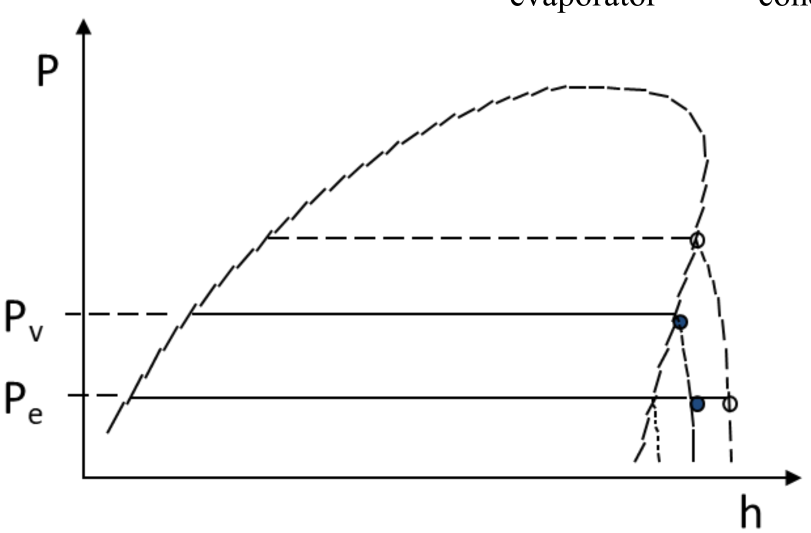
- Thermal
- Electronic expansion valve
- Float valve for shell and tube evaporator
- Typically used to control compressor superheat

Flow characteristics of compressor and capillary tube



Thermostatic Expansion Valve (TXV)





Diaphram area

$$(P_v - P_e)\,A_d = K_{spring}\,\Delta x \qquad\qquad \Delta x = (P_v - P_e)\,A_d / K_{spring}$$

Spring constant

Valve position

Direct Expansion (DX) Cooling Coils

- Similar to cooling coil covered in Lecture 10
  - Air-side analysis is identical – wet/dry coil
- Major difference: refrigerant on tube side going through a two-phase boiling/evaporation process
- Capacity rate ratio is zero

Ntu for heat & mass transfer

$$Ntu^* = \frac{U^* A_a}{\dot{m}_a}$$

Overall conductance-area product

$$A_a U^* = \frac{1}{\dfrac{c_p}{\eta_o^* h_c A_a} + \dfrac{c_s}{U_r A_r}}$$

where c_s is evaluated at refrigerant temp T_r

$$c_s \approx \frac{\Delta h_{a,sat}}{\Delta T}$$

Effectiveness for the DX coil

$$\varepsilon = 1 - e^{-Ntu^*}$$

Heat transfer rate

$$\dot{Q} = \varepsilon \, \dot{m}_a \left(h_{a,i} - h_{r,sat} \right)$$

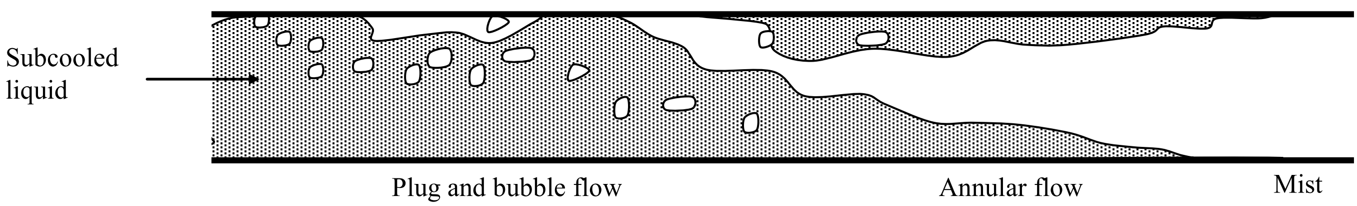
$$\dot{Q} = \dot{m}_a \left(h_{a,i} - h_{a,o} \right)$$

* As with the chilled water coil, this method yields outlet air enthalpy only. Outlet temp and humidity ratio can be determined using same method given in Lecture 13.

DX Coil Example: Determine the performance of a DX coil. The air enters the coil at a dry bulb temperature of 75 F and a wet bulb temperature of 60 F with a volume flow rate of 5000 cfm. The refrigerant is R-22 at a temperature of 40 F that enters with a quality of 0.1 and leaves with 5 F superheat. On the airside the heat transfer conductance Ua is 50 Btu/hr-ft^2 and the surface area is 360 ft^2. On the refrigerant side the heat transfer conductance Ur is 1000 Btu/hr-ft^2 and the area is 18 ft$^{2.}$

Refrigerant Heat Transfer Coefficients for DX Cooling Coils

Flow regimes during evaporation or boiling



- In DX cooling coils, refrigerant boils off inside tubes
- Refrigerant boiling involves multiple flow regimes and two interacting mechanisms:
  - Nucleate boiling at wall surface when heat flux is high or flow rate is low
  - Forced convection when flow rate is high – evaporation at liquid-vapor interface

The boiling number is a nondimensional parameter characterizing heat flux relative to mass flux

$$Bo^* = \frac{\dot{Q}''}{G\, h_{fg}} F_{FL}^{(1/0.7)}$$

where F_{FL} is a parameter related to refrigerant and tube internal surface interaction.

Values of surface parameter F_{FL} for copper tubes

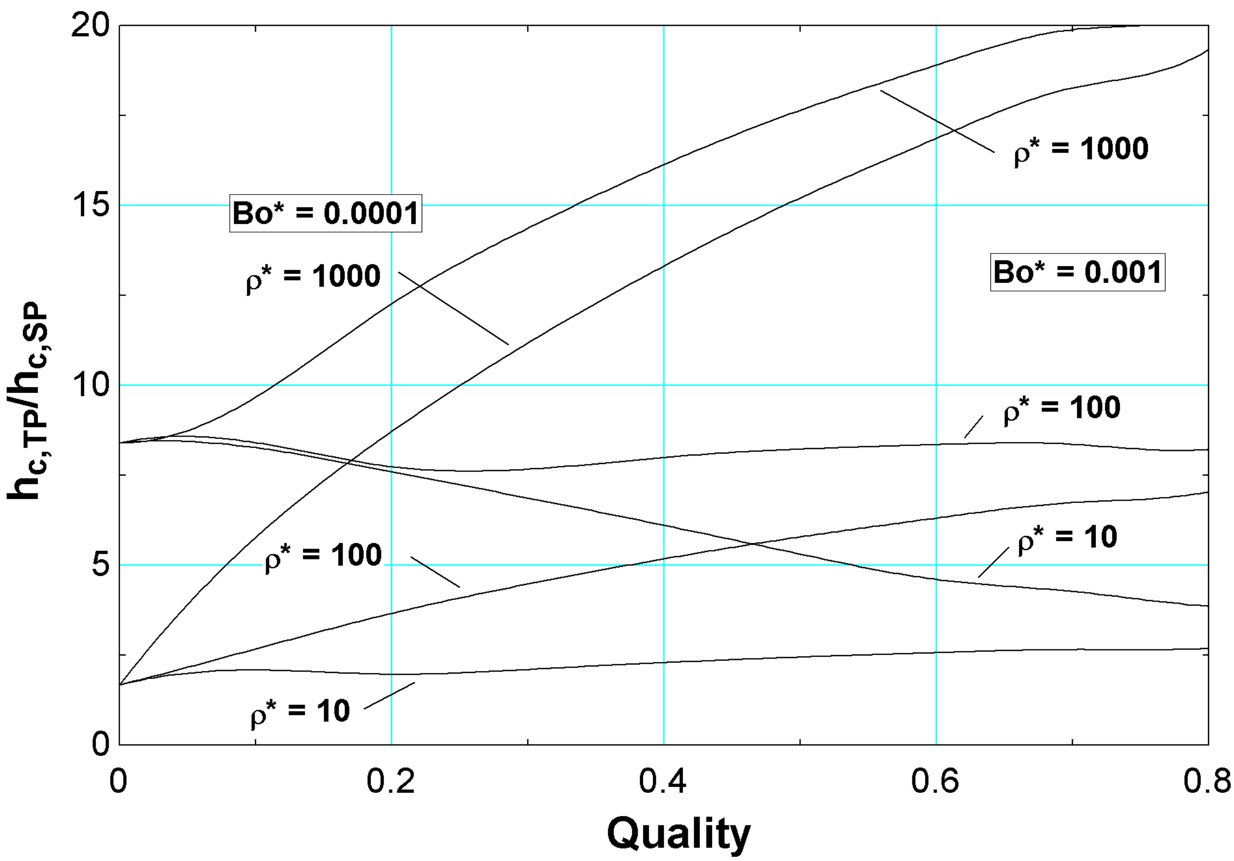
Refrigerant	F_{FL}	Refrigerant	F_{FL}
R-11	1.30	R-113	1.30
R-12	1.50	R-114	1.24
R-13B4	1.31	R-134a	1.63
R-22	2.30	R-152	1.10

Another nondimensional parameter that relates to boiling heat transfer is the ratio of the density of the liquid phase to that of the vapor phase

$$\rho^* = \frac{\rho_f}{\rho_f}$$

* Boiling heat transfer coefficient can be calculated from empirical correlations and liquid-phase heat transfer coefficient.

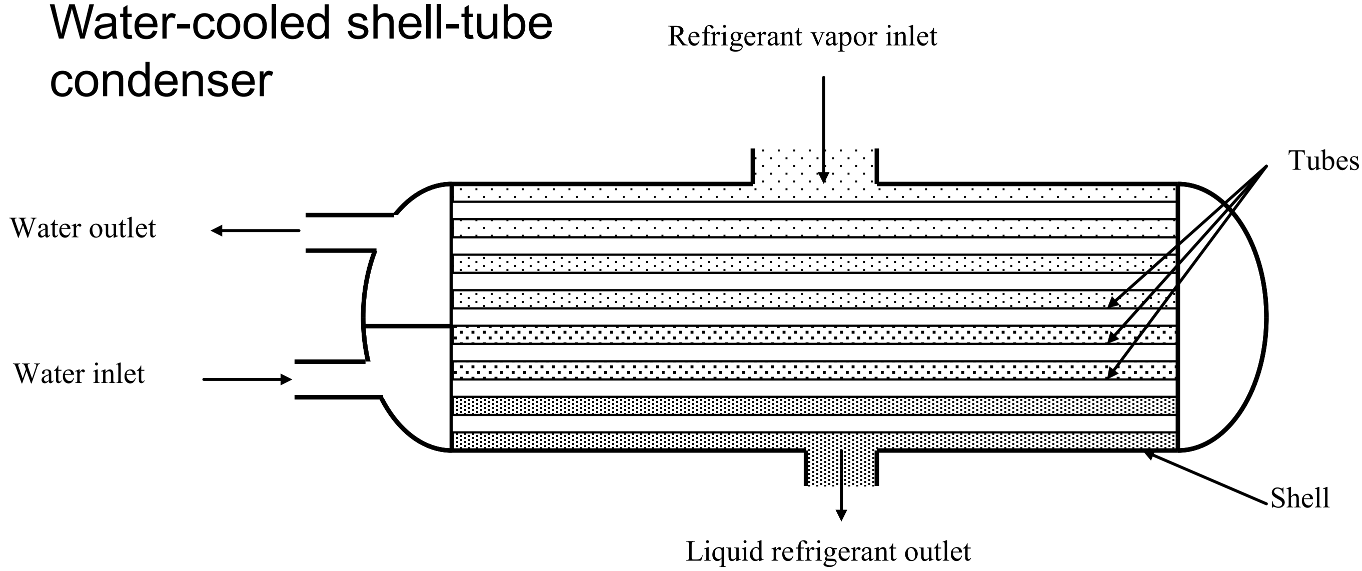
Boiling heat transfer coefficients as a function of vapor quality



Condensers

- Air-cooled or water-cooled
  - Fin-tube coil for air-cooled condenser
  - Shell-tube water-cooled condenser
- Refrigerant enters condenser in superheated vapor phase and leaves in liquid phase
- Capacity rate ratio is zero for condensation section
- Condensing temperature can be used as the inlet temperature in determining the effectiveness

Water-cooled shell-tube condenser

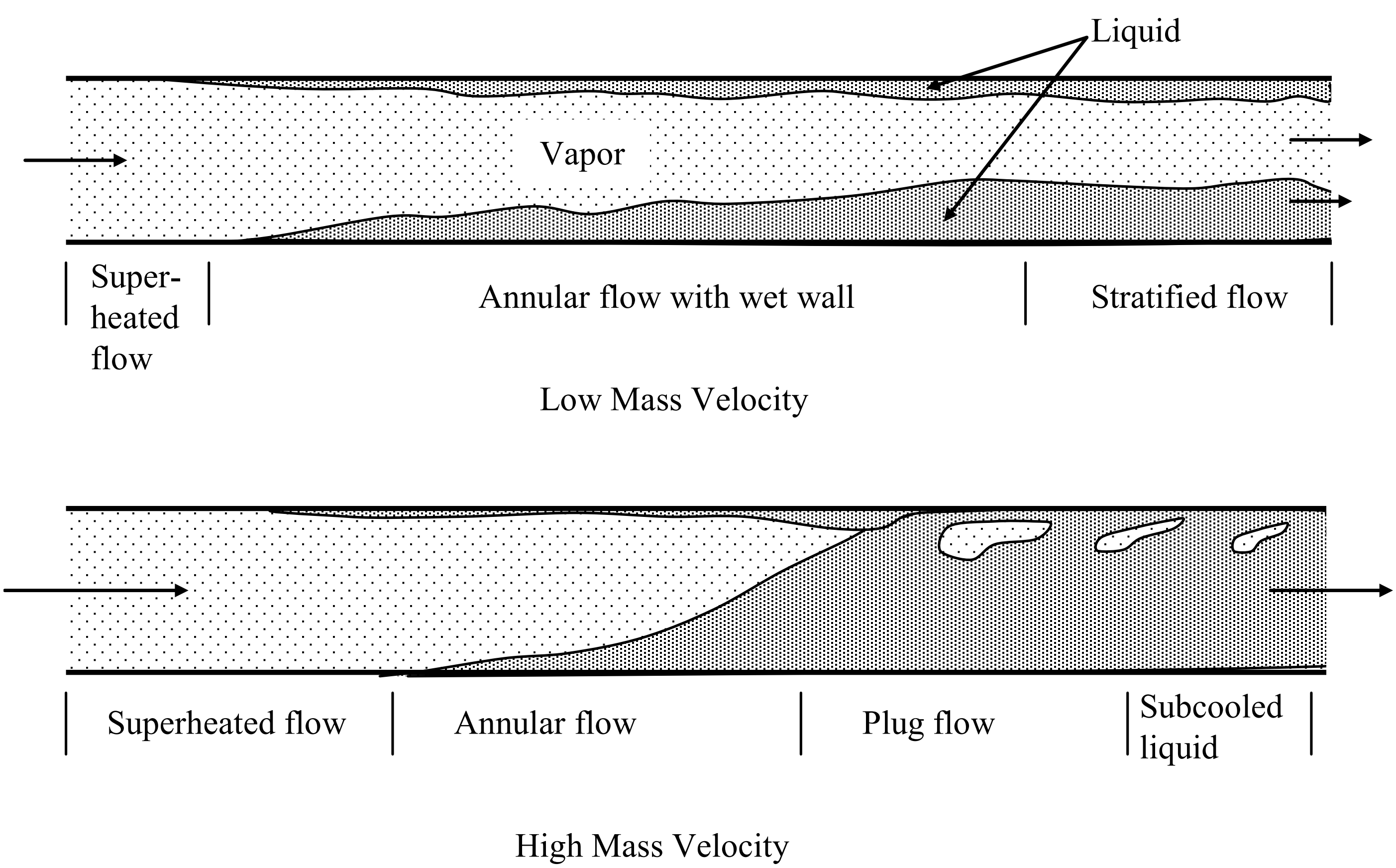


Condenser Example: A water-cooled condenser is to be designed for a flow of 0.2 kg/s of R-22 that enters at a temperature of 125 C and a pressure of 1200 kPa and leaves at 25 C. The water enters at a temperature of 17 C and has a temperature rise of 10 C. Determine the required overall heat transfer coefficient for the condenser.

Condensation Heat Transfer Coefficients inside Tubes

- Condenser tube consists of multiple flow regimes
- Condensation involves two types of heat transfer mechanisms:
  - Film condensation at the periphery of a tube
  - Convective condensation due to axial flow of condensate

Flow regimes for condensation in horizontal tubes



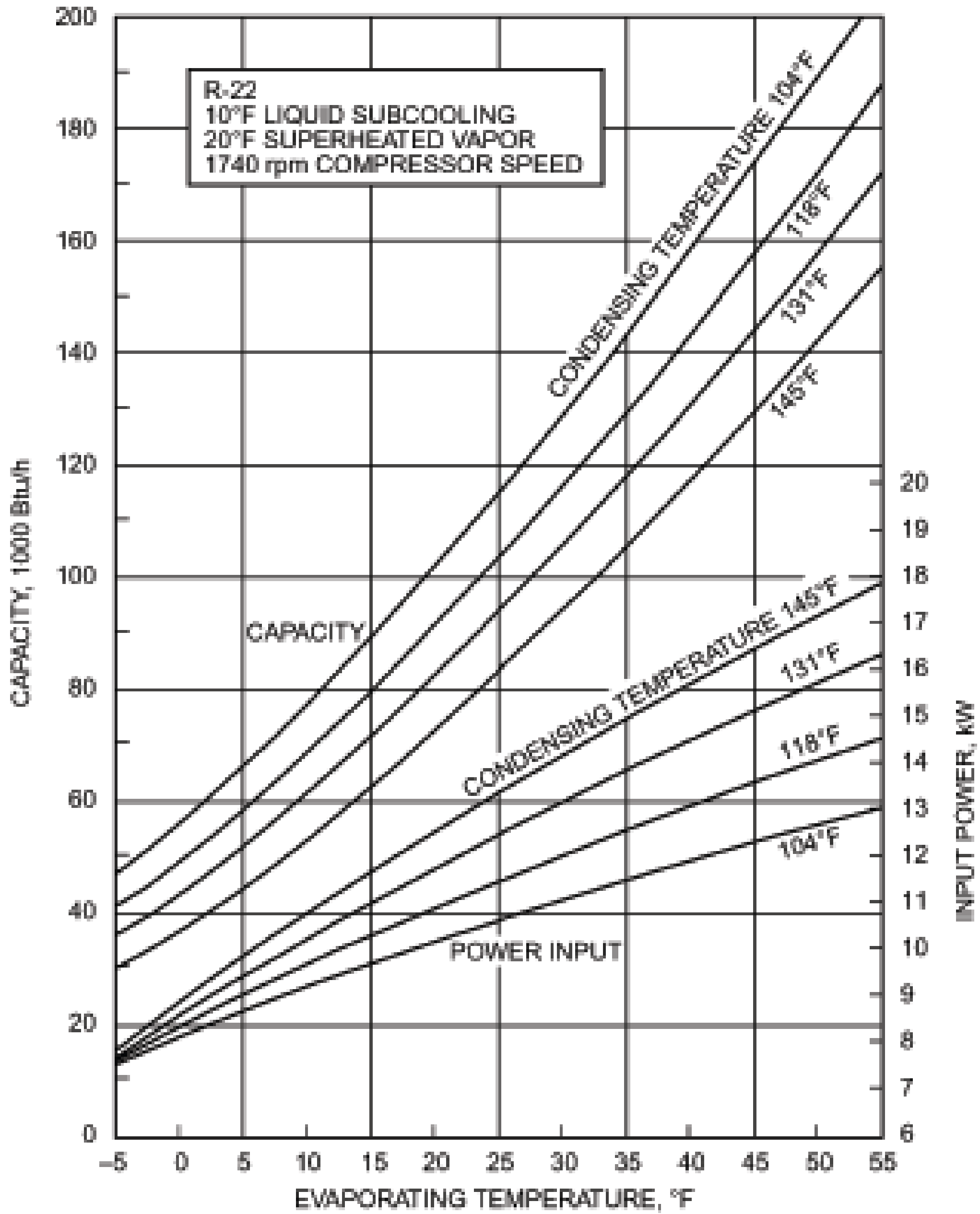
Vapor Compression System Performance

System performance metrics:

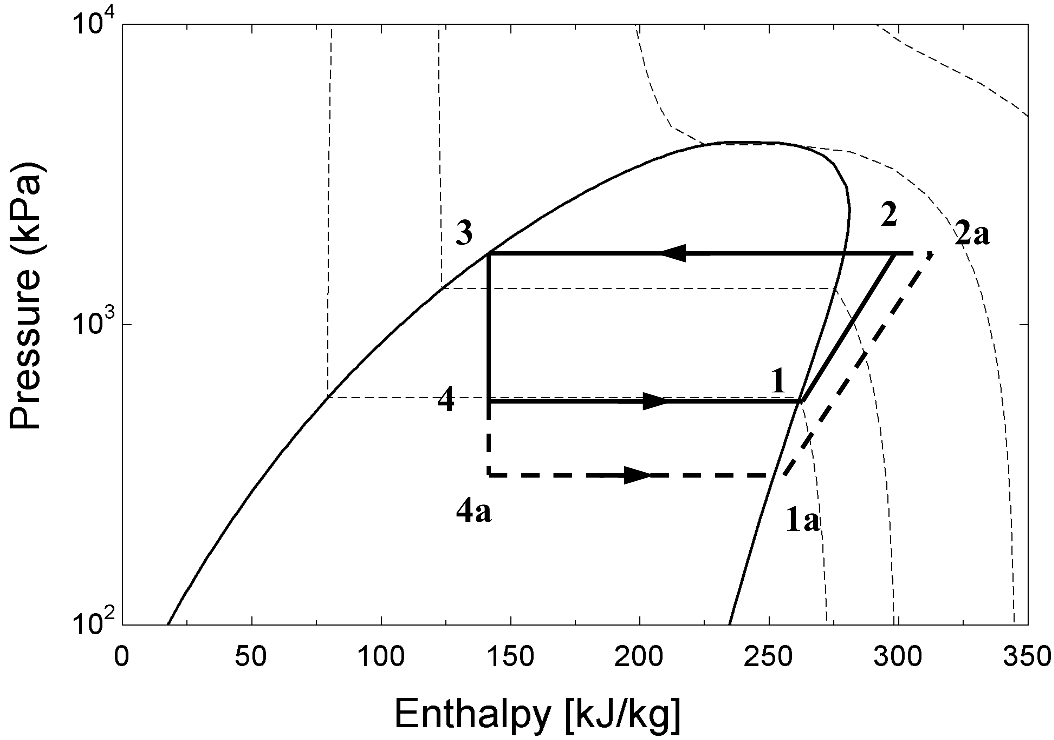
- **Capacity:** rate of cooling (or heating) energy supplied by the system
- **Power** is the amount of electricity required to run the system
- **COP** is the ratio of the capacity to the power
- **EER** (Energy Efficiency Ratio) is the same measure as COP, but with capacity in Btu/hr and power in W.
- **SEER** (Seasonal EER) is an integrated measure of performance over a whole cooling/heating season

The system instantaneous performance is dependent on evaporating and condensing temperatures, which are influenced by the environmental conditions the system works against.

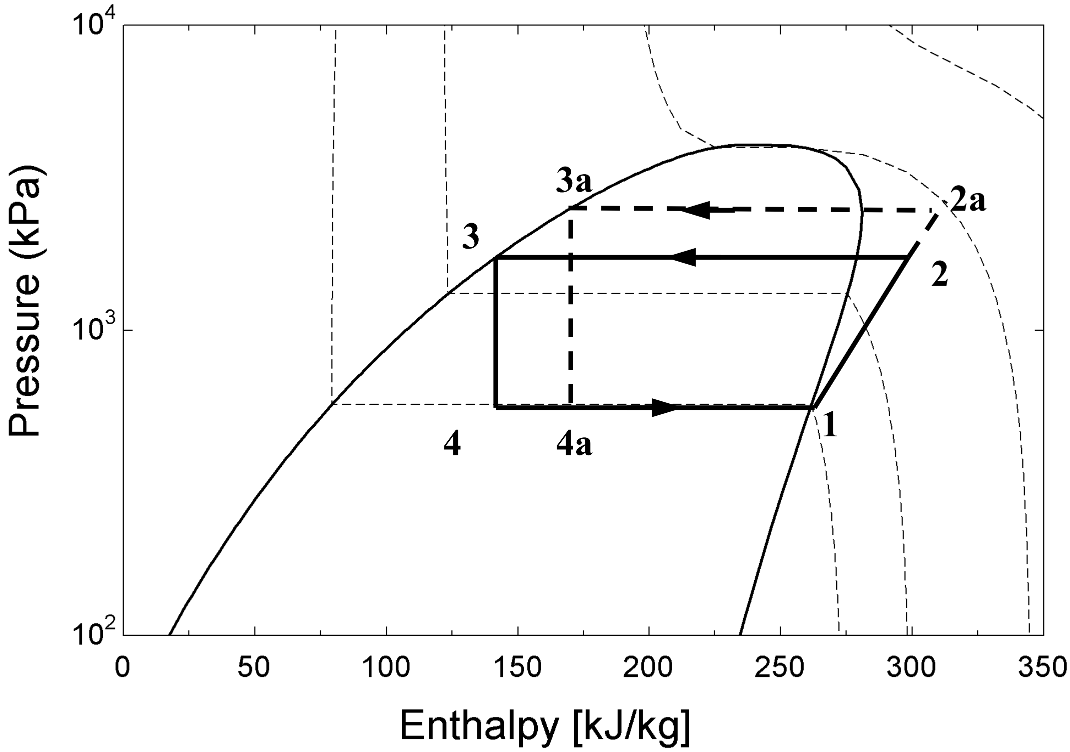
Cooling capacity and power for a refrigeration system



Process representations for two different evaporator temperatures

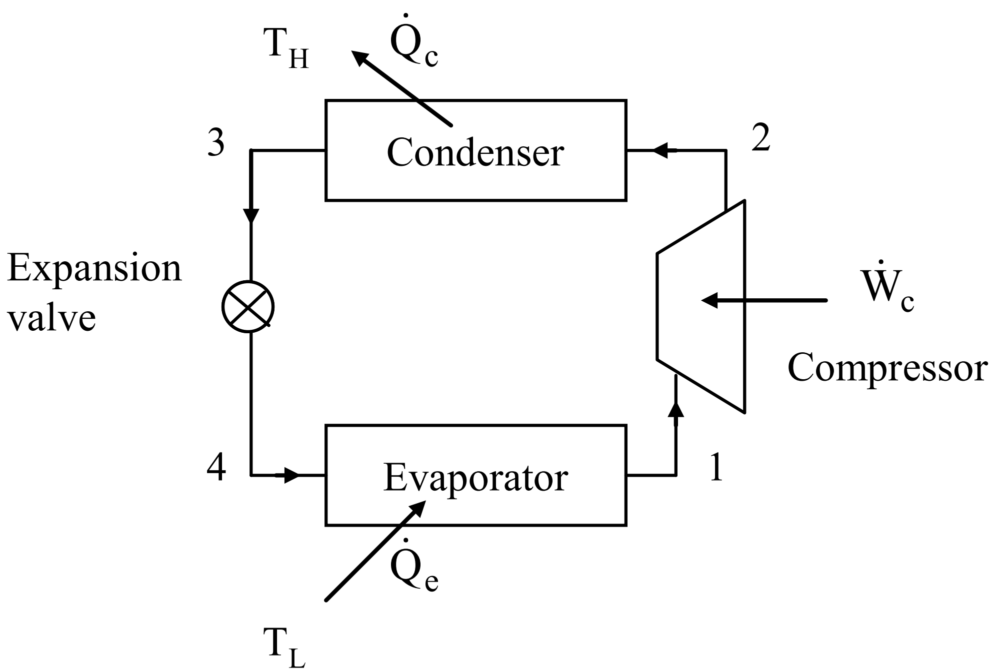


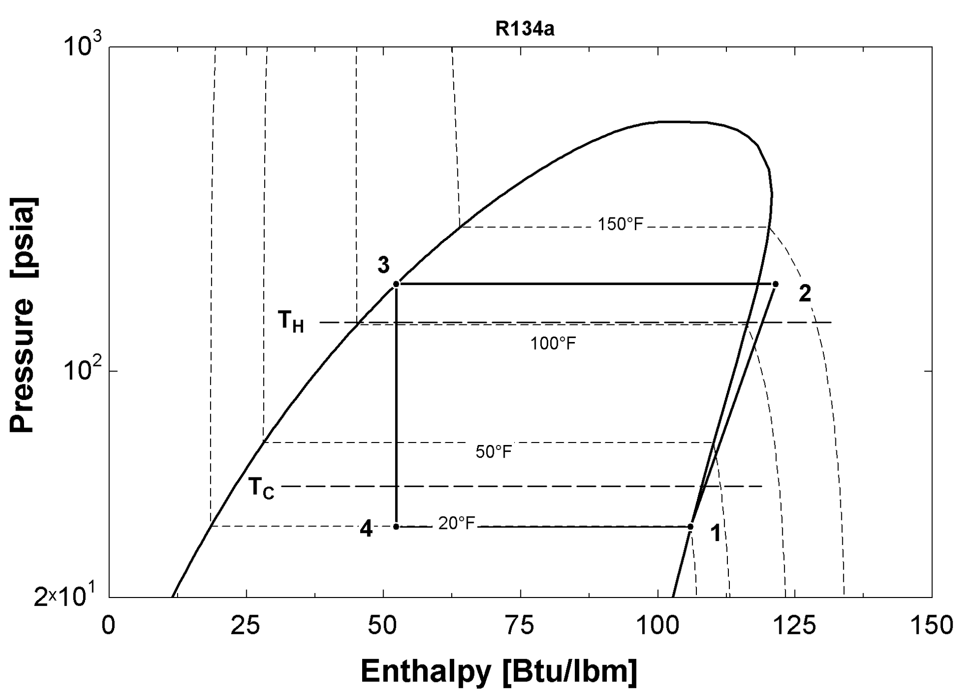
Process representation for two different condenser temperatures



System-Component Integration

Schematic and process diagram for a refrigeration system





Component Models and System Integration

Evaporator energy balance (assuming dry coil)

$$\dot{Q}_e = \epsilon_e \cdot \dot{m}_{a,e} \cdot c_{pa}(T_L - T_e)$$
$$= \dot{m}_r(h_1 - h_4)$$

Condenser energy balance

$$\dot{Q}_c = \epsilon_c \cdot \dot{m}_{a,c} \cdot c_{pa}(T_c - T_H)$$
$$= \dot{m}_r(h_2 - h_3)$$

Compressor power

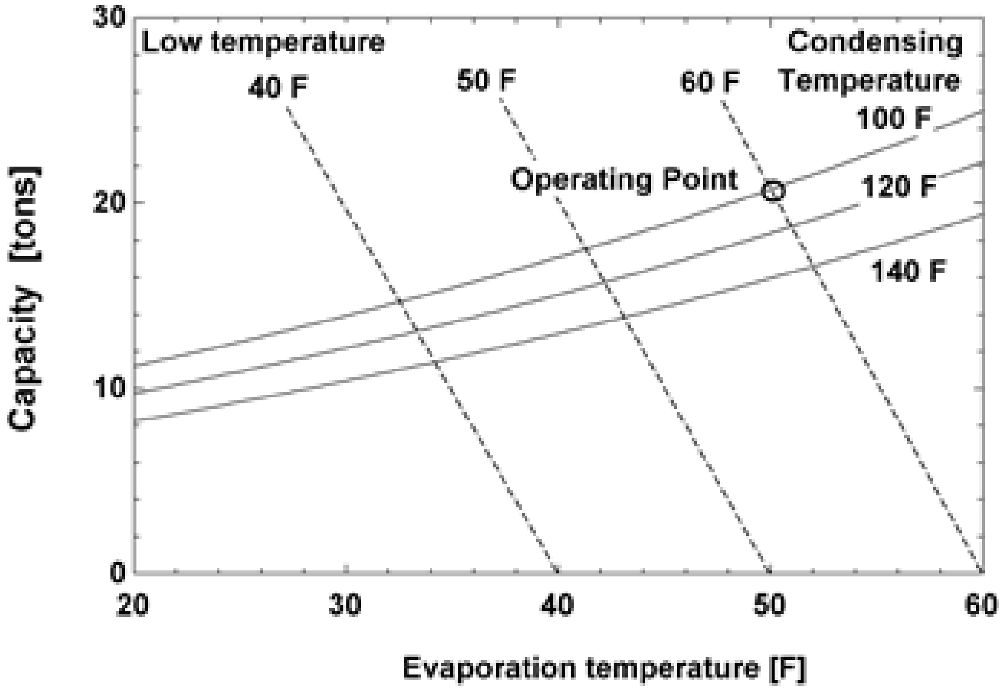
$$\dot{W} = \dot{N}\left(\frac{n}{n-1}\right)\eta_v p_e V_{disp}\left[\left(\frac{p_c}{p_e}\right)^{\frac{n}{n-1}} - 1\right]$$
$$= \dot{m}_r(h_2 - h_1)$$

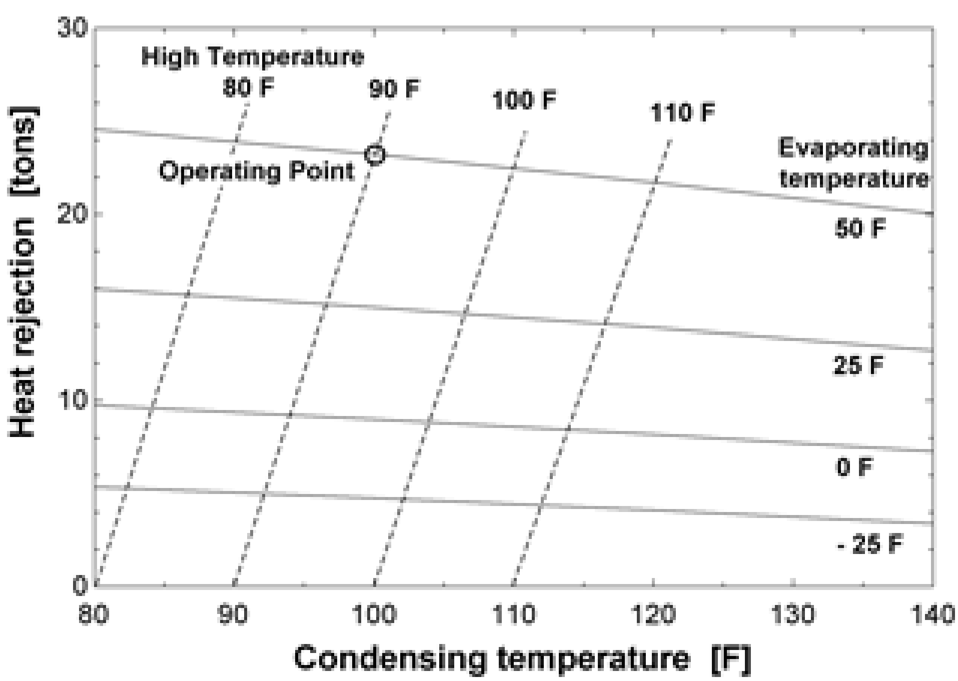
Expansion device

$$h_3 = h_4$$

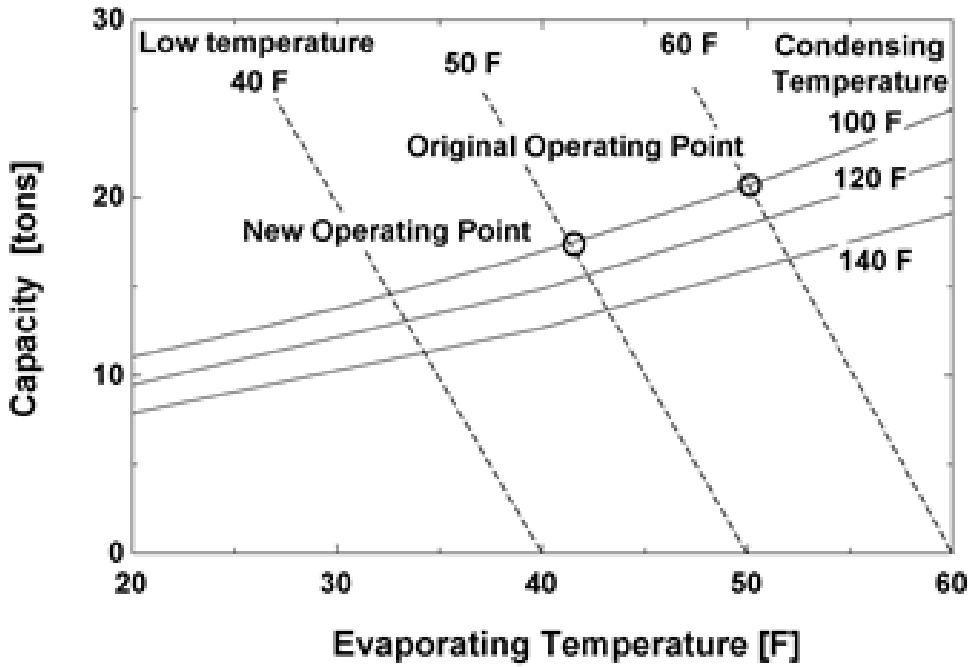
System Integration Example: Determine the balance points at design conditions for a mechanical refrigeration system. The system has a reciprocating compressor that has a displacement volume of 0.02 ft^3, a clearance volume fraction of 0.05, a rotational speed of 1740 RPM, a polytropic exponent of 1.2, and the refrigerant is R-22. The evaporator has a UAe of 36,000 Btu/hr-F and airside flow rate of 180,000 lbm/hr. The condenser UAc is 40,000 Btu/hr-F and its airside flow rate is 200,000 lbm/hr. The evaporator air inlet temperature and relative humidity are 60 F and 70%. The condenser air inlet temperature and humidity are 90 F and 40%. Refrigerant leaving the evaporator has a 5 F superheat and saturated liquid leaves the condenser. Dry evaporator coil is assumed.

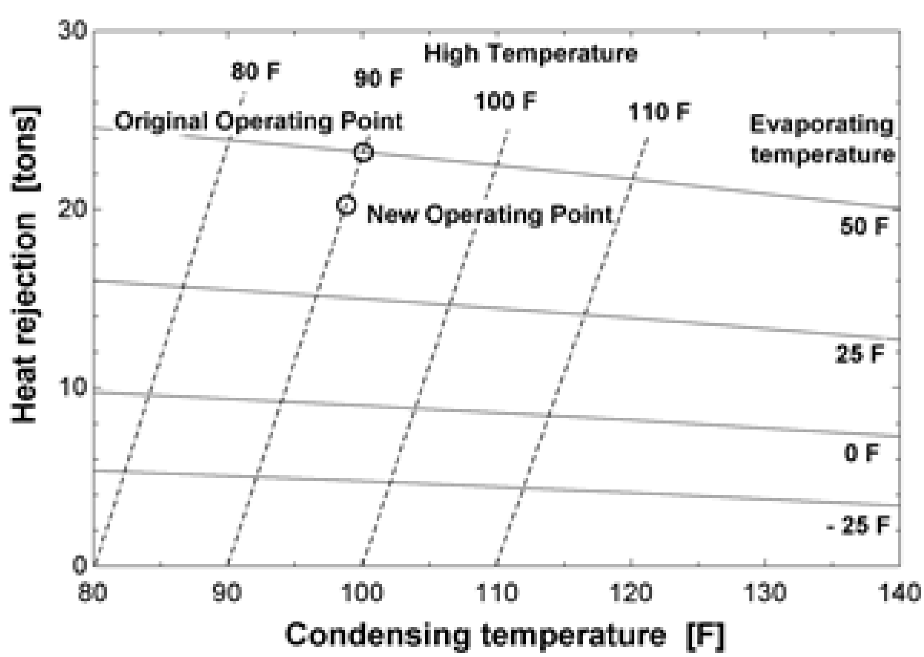
Current operating point





Operating point for low temperature reduced to 50 F





Heat Pump Systems

Heat pumps are similar to air-conditioning systems – heat is transferred from low temp to high temp

- For heat pumps, the desired output is the heat from condenser
- For air-conditioning systems, the desired output is the cooling effect by the evaporator

Heat pump COP is defined as

$$COP_{hp} = \frac{\text{Heating effect}}{\text{Energy Input}} = \frac{\dot{Q}_c}{\dot{W}_c}$$

$$COP_{hp} = \frac{\dot{Q}_c}{\dot{W}_c} = \frac{\dot{Q}_e + \dot{W}_c}{\dot{W}_c} = 1 + \frac{\dot{Q}_e}{\dot{W}_c} = 1 + COP_{AC}$$

Heating season efficiency measure is **Heating Season Performance Factor (HSPF):** estimated seasonal heating output (Btu) divided by seasonal power consumption (Watt-hr).

Common Heat Pump Configurations

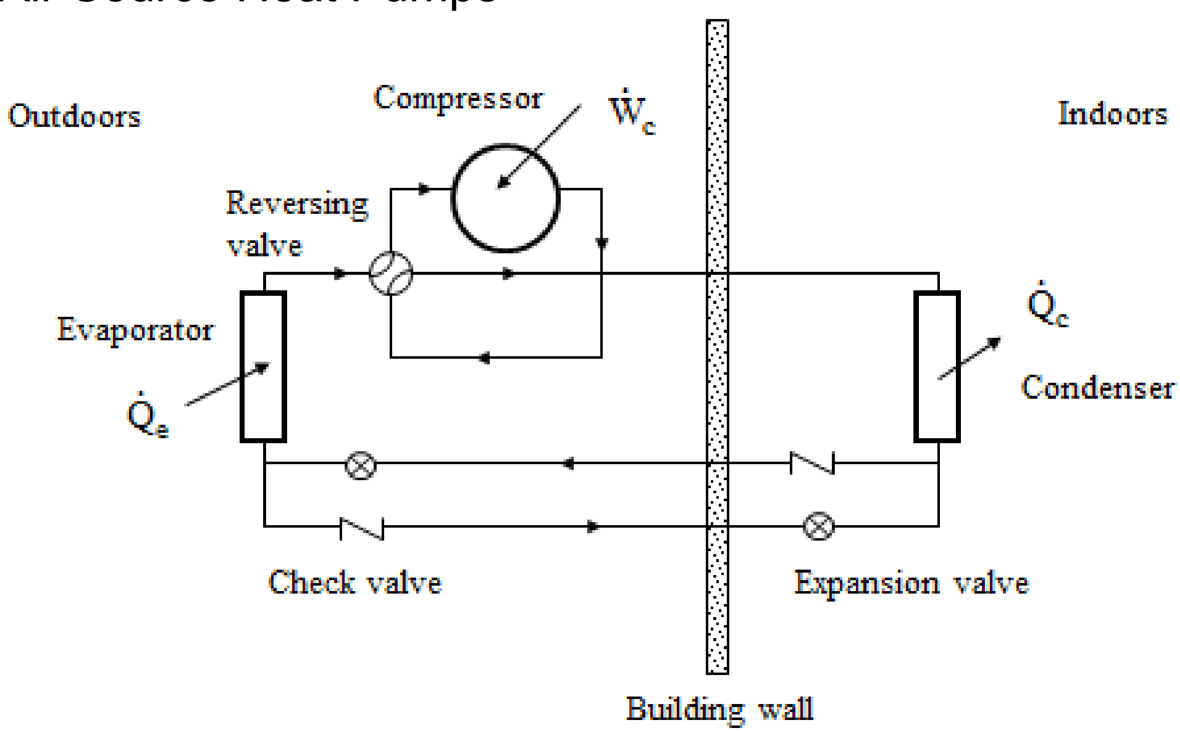
Air-to-air heat pump: heat supply is the outdoor ambient air and heat is delivered to the air inside a building

Water source heat pump: heat supply is a water loop circulating throughout a building.

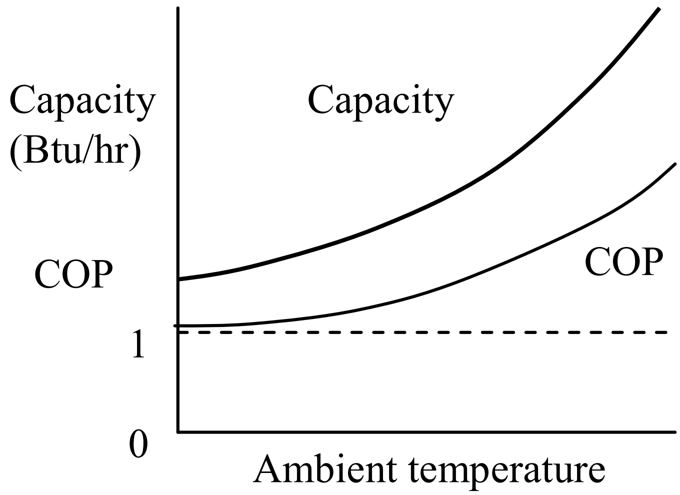
Ground source heat pump: general term for heat pump systems that use the earth, underground water, or surface water as a heat source

Ground coupled heat pump: use the earth as a heat source by circulating fluid in tubing buried in the ground

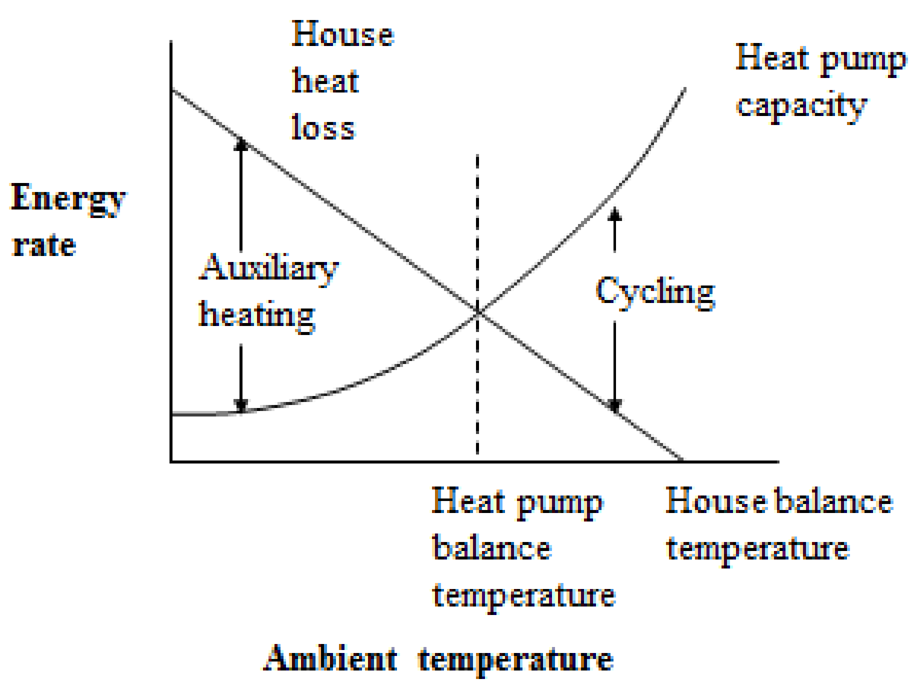
Air Source Heat Pumps



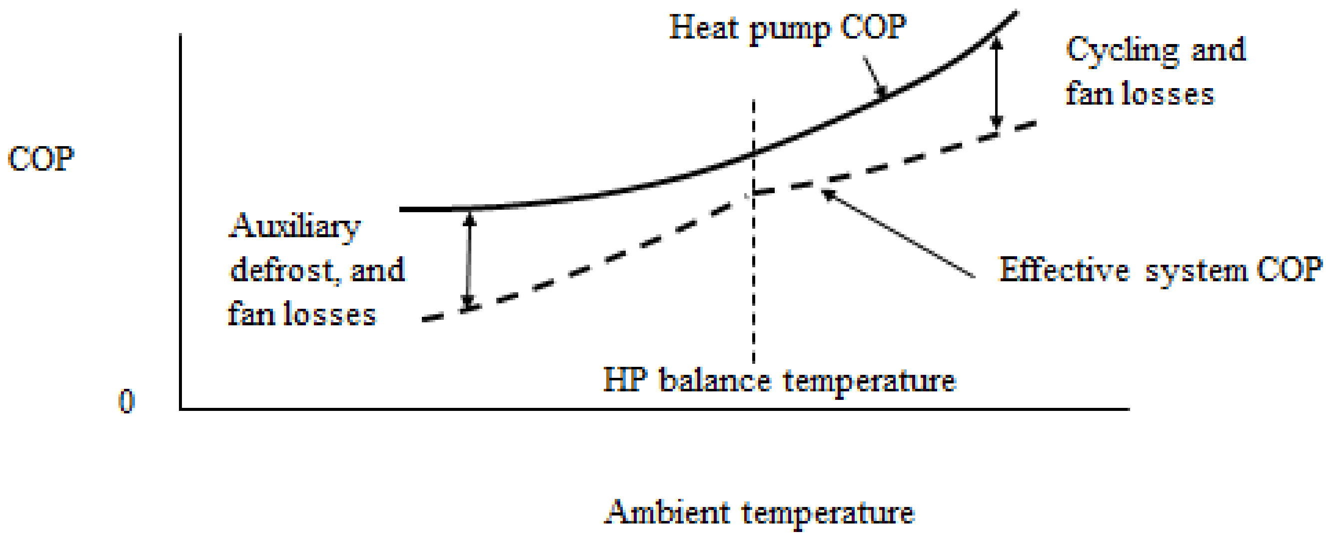
Performance characteristics for an air source heat pump



Superposition of heat pump capacity and house heating load



Heat pump and system COP as functions of ambient temperature



$$COP_{sys} = \frac{\text{Total heating rate}}{\text{Total input energy rate}} = \frac{\dot{Q}_h + \dot{W}_{f,c}}{\dot{W}_c + \dot{Q}_{aux} + \dot{W}_{f.c} + \dot{W}_{f.e}}$$

$$HSPF = \frac{\text{Annual heating energy}}{\text{Annual input energy}} = \frac{Q_h + W_{f,c}}{W_c + Q_{aux} + W_{f,c} + W_{f,e}}$$