ESO 201A: Thermodynamics
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Refrigeration Cycle

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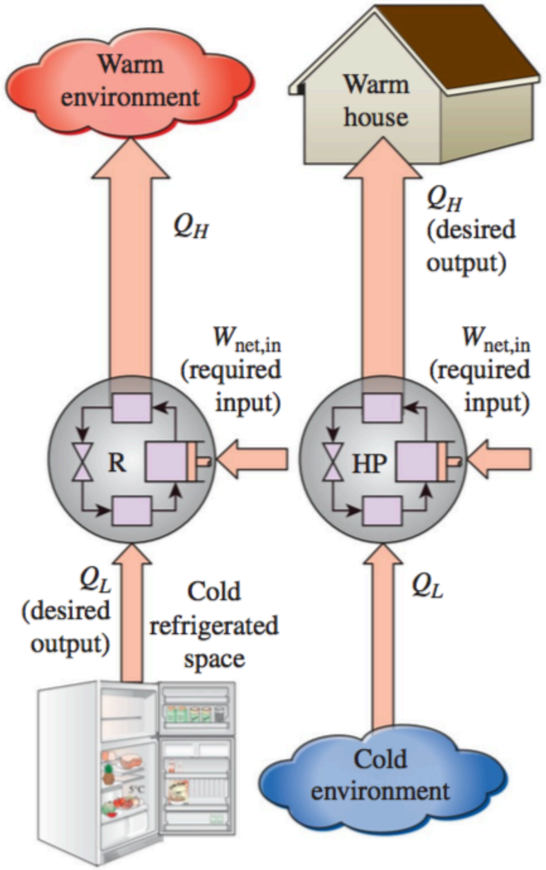
Learning Objectives

- Analyze the ideal vapor-compression refrigeration cycle.
- Analyze the actual vapor-compression refrigeration cycle.
- Review the factors involved in selecting the right refrigerant for an application.
- Discuss the operation of refrigeration and heat pump systems.
- Evaluate the performance of innovative vapor-compression refrigeration systems.

Refrigerators and Heat Pumps



(*a*) Refrigerator (*b*) Heat pump

The transfer of heat from a low-temperature region to a high-temperature one requires special devices called **refrigerators**.

Refrigerators and heat pumps are essentially the same devices; they differ in their objectives only.

$$\text{COP}_\text{R} = \frac{\text{Desired output}}{\text{Required input}} = \frac{\text{Cooling effect}}{\text{Work input}} = \frac{Q_L}{W_{\text{net,in}}}$$

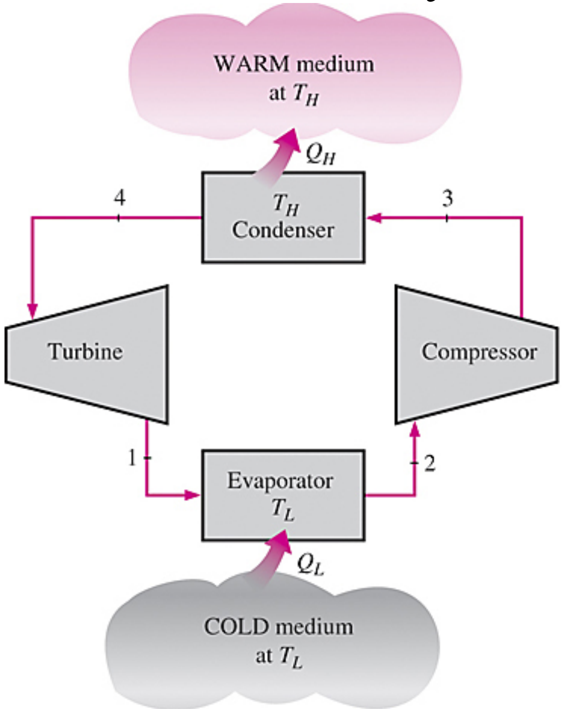
$$\text{COP}_\text{HP} = \frac{\text{Desired output}}{\text{Required input}} = \frac{\text{Heating effect}}{\text{Work input}} = \frac{Q_H}{W_{\text{net,in}}}$$

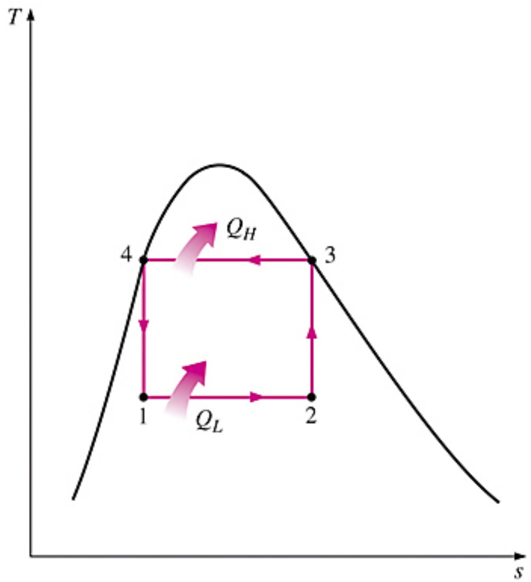
$$\text{COP}_\text{HP} = \text{COP}_\text{R} + 1$$ for fixed values of Q_L and Q_H

The objective of a refrigerator is to remove heat (Q_L) from the cold medium; the objective of a heat pump is to supply heat (Q_H) to a warm medium.

The Reverse Carnot Cycle

Reverse Carnot cycle executed within saturation dome of a refrigerant





$$\mathrm{COP}_{\mathrm{R,Carnot}} = \frac{1}{T_H/T_L - 1}$$

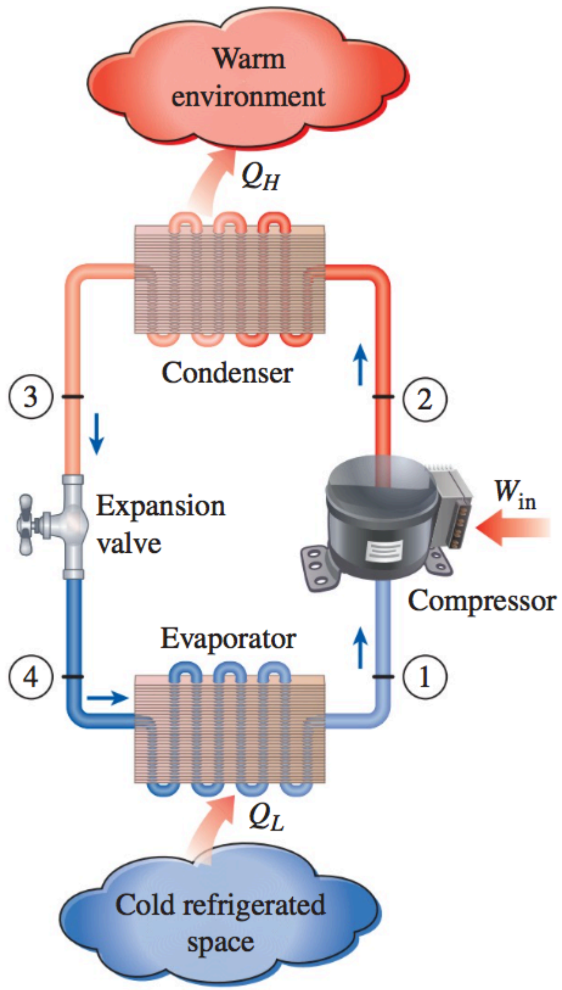
$$\mathrm{COP}_{\mathrm{HP,Carnot}} = \frac{1}{1 - T_L/T_H}$$

Difficulties:

- 2-3-requires compressor to handle two phases
- 4-1 expansion of high moisture content refrigerant in a turbine
- Difficulty in maintaining isothermal conditions at boiler and evaporator if executed outside the saturation region.

The ideal vapor-compression refrigeration cycle

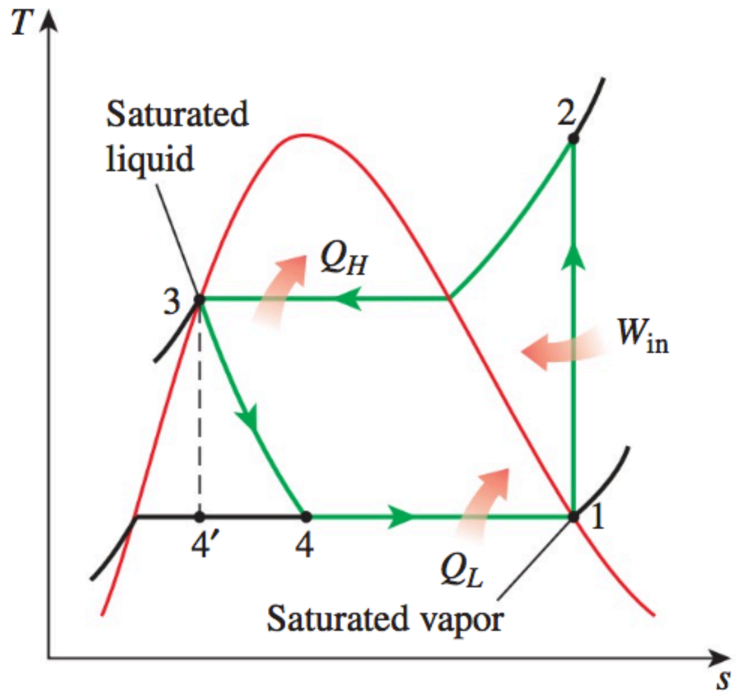
- Vaporize the refrigerant completely before it is compressed
- Refrigerants enters compressor as sat vapor and exit condenser as sat liquid
- Replace turbine by a throttling valve (expansion valve or capillary tube
- It gets expanded using valve and exist as low quality sat mix.



The ideal vapor-compression refrigeration cycle involves an irreversible (throttling) process

The ideal vapor-compression refrigeration cycle

1-2 Isentropic compression in a compressor
2-3 Constant-pressure heat rejection in a condenser
3-4 Throttling in an expansion device
4-1 Constant-pressure heat absorption in an evaporator



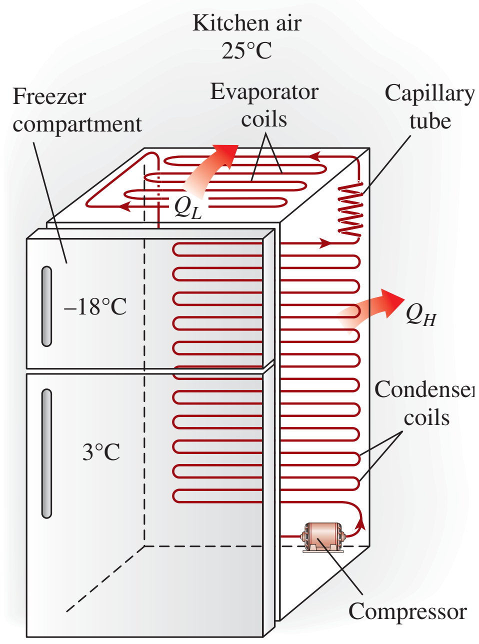
Replacing the expansion valve by a turbine is not practical since the added benefits cannot justify the added cost and complexity.

This is the most widely used cycle for refrigerators, A-C systems, and heat pumps.

COP increase by 2 to 4 percent for each C the evaporating temp is raised or condensing temperature is lowered

Ideal vapor compression refrigeration cycle : p-h diagram

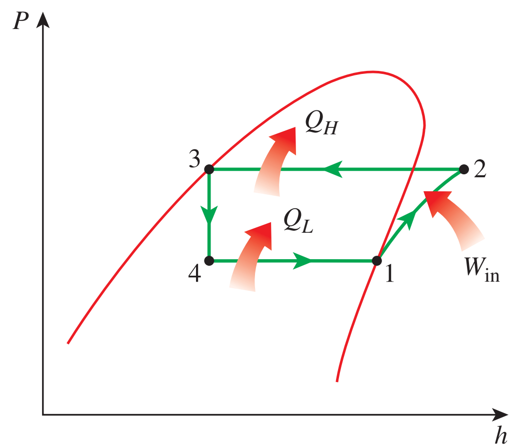
All four components associated with the vapor-compression refrigeration cycle are steady-flow devices



- The condenser and the evaporator do not involve any work
- Compressor can be approximated as adiabatic

Steady state flow energy balance

$$(q_{in} - q_{out}) + (w_{in} - w_{out}) = h_e - h_i$$

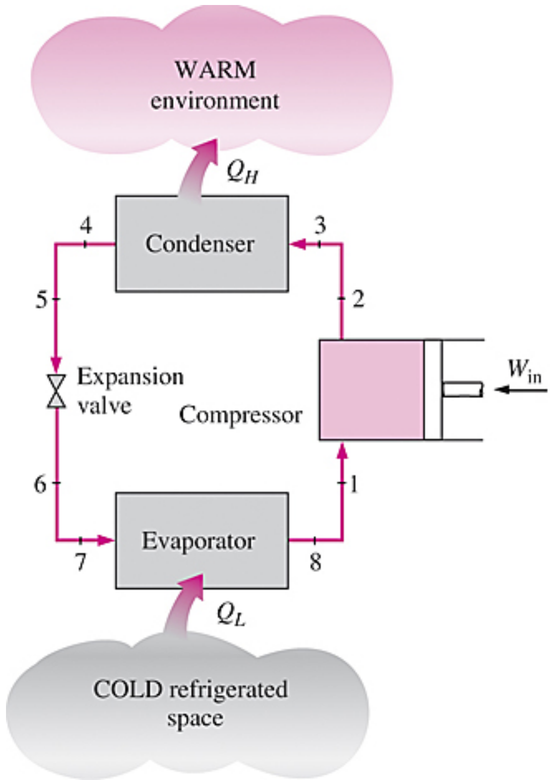


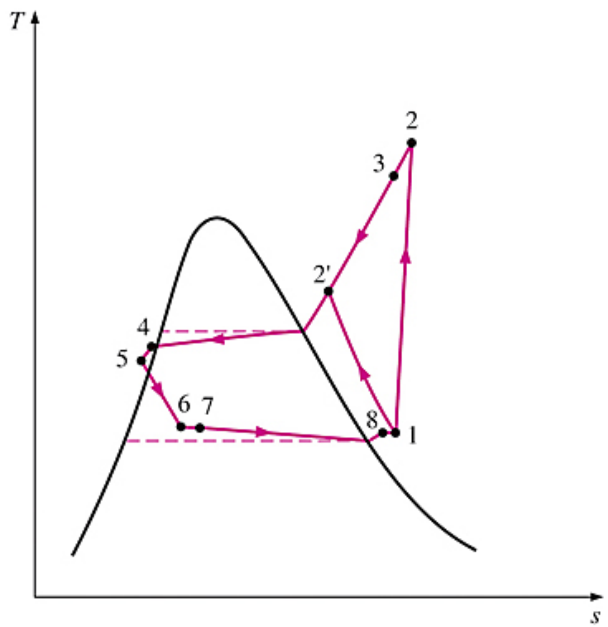
$$\mathrm{COP_R} = \frac{q_L}{w_{net,in}} = \frac{h_1 - h_4}{h_2 - h_1} \qquad \mathrm{COP_{HP}} = \frac{q_H}{w_{net,in}} = \frac{h_2 - h_3}{h_2 - h_1}$$

$h_1 = h_{g\,@\,P_1}$ and $h_3 = h_{f\,@\,P_3}$ for the ideal case

Deviation from ideal vapor-compression refrigeration cycle

An actual vapor-compression refrigeration cycle differs from the ideal one in several ways, owing mostly to the irreversibilities that occur in various components, mainly due to fluid friction (causes pressure drops) and heat transfer to or from the surroundings. The COP decreases as a result of irreversibilities.





DIFFERENCES

Non-isentropic compression

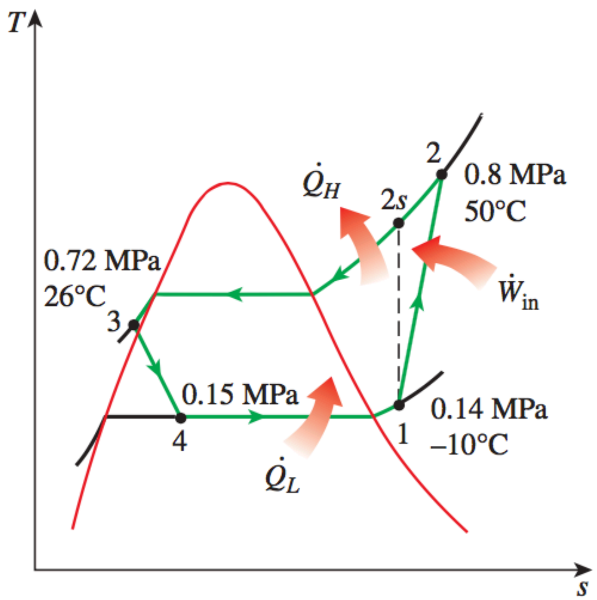
Superheated vapor at evaporator exit

Subcooled liquid at condenser exit

Pressure drops in condenser and evaporator

Example

Refrigerant-134a enters the compressor of a refrigerator as superheated vapor at 0.14 MPa and -10°C at a rate of 0.05 kg/s and leaves at 0.8 MPa and 50°C. The refrigerant is cooled in the condenser to 26°C and 0.72 MPa and is throttled to 0.15 MPa. Disregarding any heat transfer and pressure drops in the connecting lines between the components, determine (a) the rate of heat removal from the refrigerated space and the power input to the compressor, (b) the isentropic efficiency of the compressor, and (c) the coefficient of performance of the refrigerator.



For solution see the example 11.2 of the text book

The enthalpies of the refrigerant at various states are determined from the refrigerant tables, and are:

$$\left.\begin{array}{l} P_1 = 0.14 \text{ MPa} \\ T_1 = -10^\circ\text{C} \end{array}\right\} \quad h_1 = 246.36 \text{ kJ/kg}$$

$$\left.\begin{array}{l} P_2 = 0.8 \text{ MPa} \\ T_2 = 50^\circ\text{C} \end{array}\right\} \quad h_2 = 286.69 \text{ kJ/kg}$$

$$\left.\begin{array}{l} P_3 = 0.72 \text{ MPa} \\ T_3 = 26^\circ\text{C} \end{array}\right\} \quad h_3 \cong h_{f\,@\,26^\circ\text{C}} = 87.83 \text{ kJ/kg}$$

$$h_4 \cong h_3 \text{ (throttling)} \longrightarrow h_4 = 87.83 \text{ kJ/kg}$$

a) The rate of heat removal from the refrigerated space and the power input to the compressor are determined from their definitions:

$$\dot{Q}_L = \dot{m}(h_1 - h_4) = (0.05 \text{ kg/s})[(246.36 - 87.83) \text{ kJ/kg}] = 7.93 \text{ kW}$$

and

$$\dot{W}_{\text{in}} = \dot{m}(h_2 - h_1) = (0.05 \text{ kg/s})[(286.69 - 246.36) \text{ kJ/kg}] = 2.02 \text{ kW}$$

(b) The isentropic efficiency of the compressor is determined from

$$\eta_C \cong \frac{h_{2s} - h_1}{h_2 - h_1}$$

where the enthalpy at state 2s (P_{2s} = 0.8 MPa and $s_{2s} = s_1$ = 0.9724 kJ/kg·K) is 284.21 kJ/kg. Thus,

$$\eta_C = \frac{284.21 - 246.36}{286.69 - 246.36} = \mathbf{0.939 \text{ or } 93.9\%}$$

(c) The coefficient of performance of the refrigerator is

$$\text{COP}_\text{R} = \frac{\dot{Q}_L}{\dot{W}_\text{in}} = \frac{7.93 \text{ kW}}{2.02 \text{ kW}} = 3.93$$

Selecting the right refrigerants

- Several refrigerants may be used in refrigeration systems such as chlorofluorocarbons (CFCs), ammonia, hydrocarbons (propane, ethane, ethylene, etc.), carbon dioxide, air (in the air-conditioning of aircraft), and even water (in applications above the freezing point).
- R-11, R-12, R-22, R-134a, and R-502 account for over 90 percent of the market.
- The industrial and heavy-commercial sectors use *ammonia* (it is toxic).
- R-11 is used in large-capacity water chillers serving A-C systems in buildings.
- R-134a (replaced R-12, which damages ozone layer) is used in domestic refrigerators and freezers, as well as automotive air conditioners.
- R-22 is used in window air conditioners, heat pumps, air conditioners of commercial buildings, and large industrial refrigeration systems, and offers strong competition to ammonia.
- R-502 (a blend of R-115 and R-22) is the dominant refrigerant used in commercial refrigeration systems such as those in supermarkets.
- CFCs allow more ultraviolet radiation into the earth's atmosphere by destroying the protective ozone layer and thus contributing to the greenhouse effect that causes global warming. Fully halogenated CFCs (such as R-11, R-12, and R-115) do the most damage to the ozone layer. Refrigerants that are friendly to the ozone layer have been developed.
- Two important parameters that need to be considered in the selection of a refrigerant are the temperatures of the two media (the refrigerated space and the environment) with which the refrigerant exchanges heat.

Innovative vapor-compression refrigeration cycle

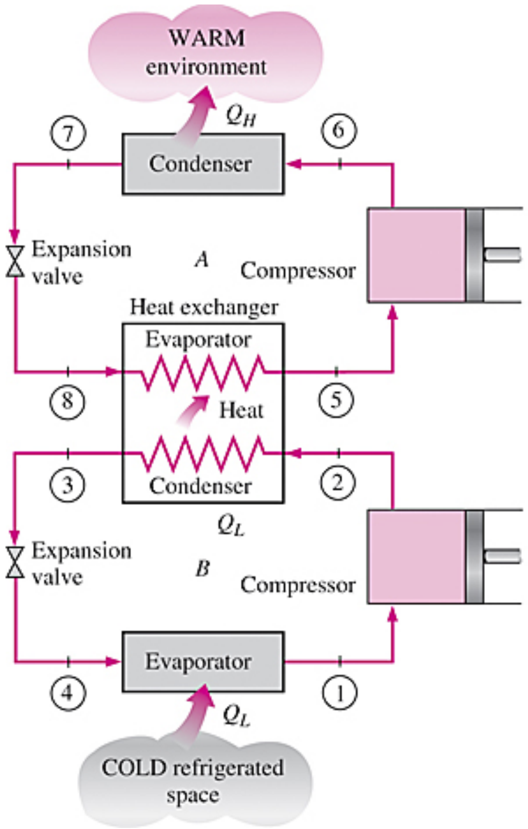
- The simple vapor-compression refrigeration cycle is the most widely used refrigeration cycle, and it is adequate for most refrigeration applications.
- The ordinary vapor-compression refrigeration systems are simple, inexpensive, reliable, and practically maintenance-free.
- However, for large industrial applications *efficiency,* not simplicity, is the major concern.
- Also, for some applications the simple vapor-compression refrigeration cycle is inadequate and needs to be modified.
- For moderately and very low temperature applications some innovative refrigeration systems are used:
  - Cascade refrigeration systems
  - Multistage compression refrigeration systems
  - Multipurpose refrigeration systems with a single compressor
  - Liquefaction of gases

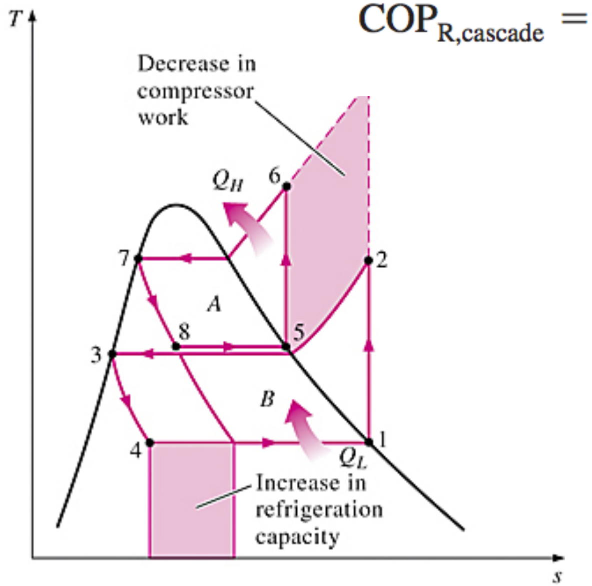
Cascade refrigeration system

Some industrial applications require moderately low temperatures, and the temperature range they involve may be too large for a single vapor-compression refrigeration cycle to be practical. The solution is **cascading.**

$$\dot{m}_A(h_5 - h_8) = \dot{m}_B(h_2 - h_3) \longrightarrow \frac{\dot{m}_A}{\dot{m}_B} = \frac{h_2 - h_3}{h_5 - h_8}$$

$$\text{COP}_{\text{R,cascade}} = \frac{\dot{Q}_L}{\dot{W}_{\text{net,in}}} = \frac{\dot{m}_B(h_1 - h_4)}{\dot{m}_A(h_6 - h_5) + \dot{m}_B(h_2 - h_1)}$$





A two-stage cascade refrigeration system with the same refrigerant in both stages.

Cascading improves the COP of a refrigeration system.

Some systems use three or four stages of cascading.

Summary

- Refrigerators and Heat Pumps
- The Reversed Carnot Cycle
- The Ideal Vapor-Compression Refrigeration Cycle
- Actual Vapor-Compression Refrigeration Cycle
- Selecting the Right Refrigerant
- Innovative Vapor-Compression Refrigeration Systems