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Refrigeration and the Vapor Compression Cycle

E134 – Running a Rankine cycle backwards for fun and profit

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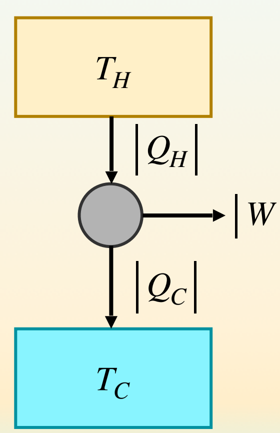
In a heat engine you want to generate work. You do so by converting as much of the high-temperature heat as possible into work. The efficiency of any heat engine operating between two heat reservoirs is defined as:

$$\eta \equiv \frac{|W|}{|Q_H|}$$

Again, it's what you want divided by what you pay for. The efficiency of a Carnot engine is

$$\eta = \frac{|W|}{|Q_H|} = 1 - \frac{T_C}{T_H}$$



In a refrigerator, we want to remove heat at a cold temperature. We do so by putting in work. The coefficient of performance for a refrigerator is the heat removed at the low temperature divided by the work that you have to put in,

$$\omega \equiv \frac{|Q_C|}{|W|} = \text{C.O.P.}$$

Again, it's what you want divided by what you pay for. The coefficient of performance for a Carnot refrigerator is

$$\omega = \frac{|Q_C|}{|W|} = \frac{T_C}{T_H - T_C}$$

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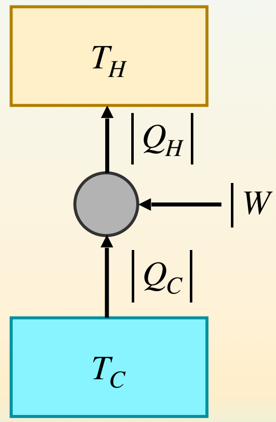

In a heat pump, we want to supply heat at a warm temperature. We do so by putting in work. The coefficient of performance for a heat pump is the heat supplied at the warm temperature divided by the work that you have to put in,

$$\omega \equiv \frac{|Q_H|}{|W|} = \text{C.O.P.}$$

Again, it's what you want divided by what you pay for. The coefficient of performance for a Carnot heat pump is

$$\omega = \frac{|Q_H|}{|W|} = \frac{T_H}{T_H - T_C}$$

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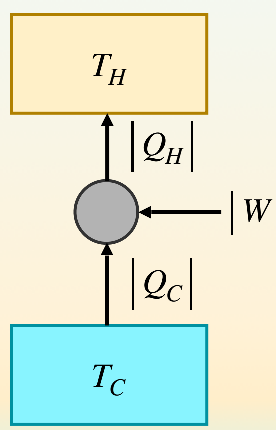

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Given the coefficients of performance for a Carnot refrigerator

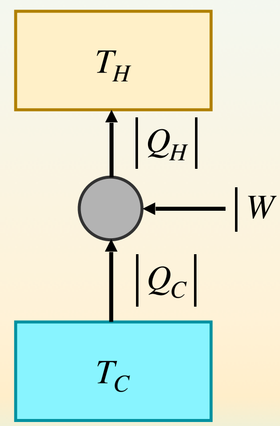
$$\omega = \frac{|Q_C|}{|W|} = \frac{T_C}{T_H - T_C}$$

and a Carnot heat pump

$$\omega = \frac{|Q_H|}{|W|} = \frac{T_H}{T_H - T_C}$$

what are the trends in ω with ΔT ?

Do they work best when ΔT is big or small?



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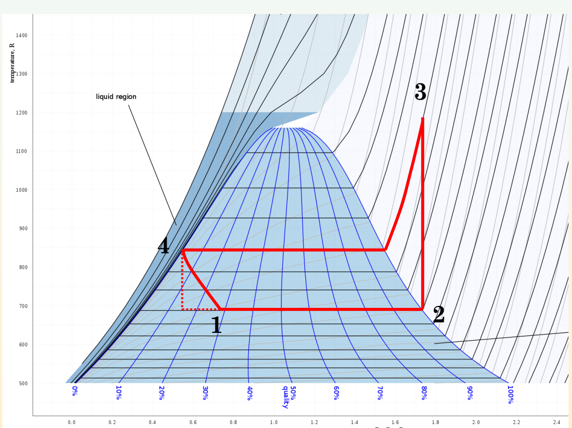
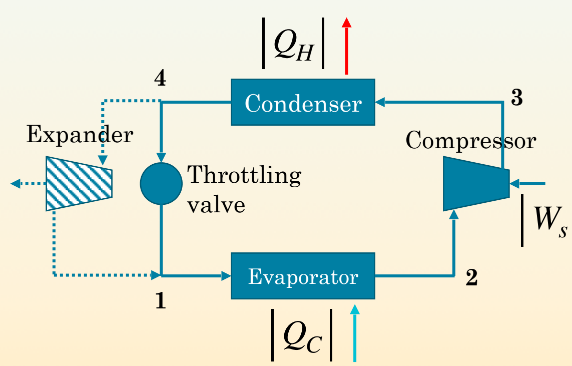
Vapor Compression Cycle





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Evaporator

$$\dot{Q}_C = \dot{m}\Delta H = \dot{m}\left(H_2 - H_1\right)$$

Inlet enthalpy comes from isenthalpic valve.

Outlet enthalpy is saturated vapor at T_2, P_2.

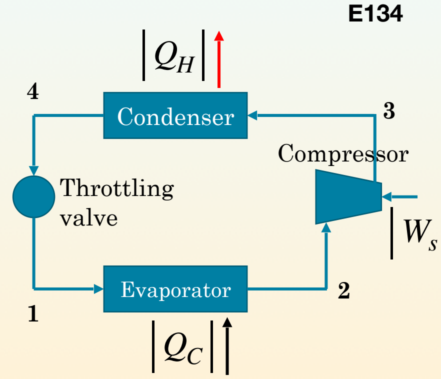
Compressor

$$\dot{W}_s = \dot{m}\Delta H = \dot{m}\left(H_3 - H_2\right)$$

$$\Delta\dot{S} = 0 \Rightarrow S_3 = S_2$$

Inlet enthalpy, entropy is from saturated vapor at T_2, P_2.

Outlet enthalpy comes from property table at P_3, S_3.



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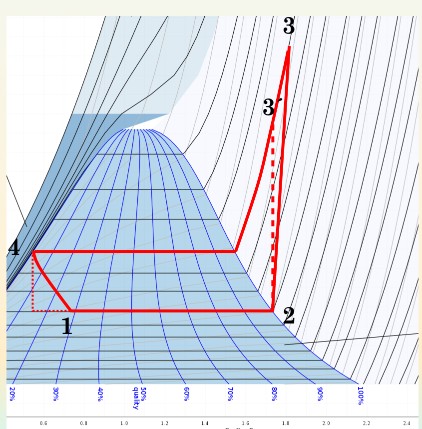
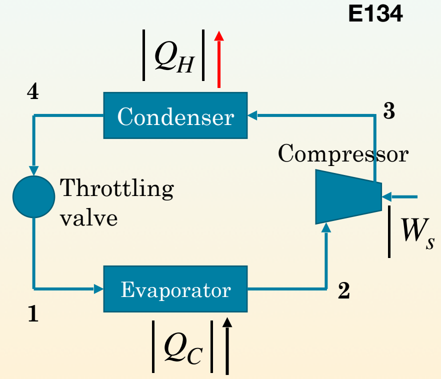
Compressor (cont.)

Any real compressor will not be isentropic, but will have an efficiency

$$\eta_{\text{comp}} = \frac{\dot{W}_{s\text{ isen}}}{\dot{W}_{s\text{ actual}}}$$





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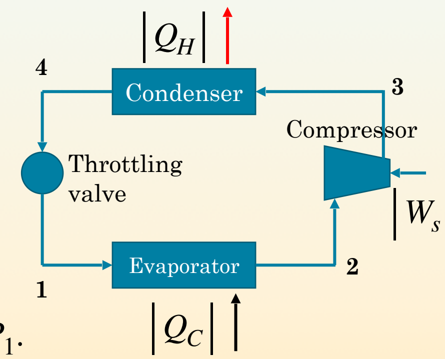
Condenser

$$\dot{Q}_H = \dot{m}\Delta H = \dot{m}\left(H_4 - H_3\right)$$

Inlet enthalpy comes from compressor.

Outlet enthalpy is saturated liquid at T_4, P_4.



Throttling Valve

$$\Delta\dot{H} = 0 \Rightarrow H_1 = H_4$$

Outlet quality comes from property table at T_1, P_1.

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Calculating ω

$$\left|Q_C\right| = H_2 - H_1$$

$$\left|Q_H\right| = H_3 - H_4$$

$$\left|W_s\right| = \left|Q_H\right| - \left|Q_C\right|$$

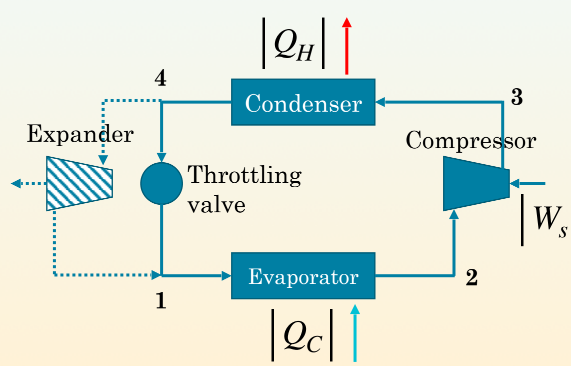
$$\left|W_s\right| = \left(H_3 - H_4\right) - \left(H_2 - H_1\right)$$

For expander, $H_4 \neq H_1$

$$\omega = \frac{H_2 - H_1}{\left(H_3 - H_4\right) - \left(H_2 - H_1\right)}$$

For valve, $H_4 = H_1$

$$\omega = \frac{H_2 - H_1}{H_3 - H_2}$$



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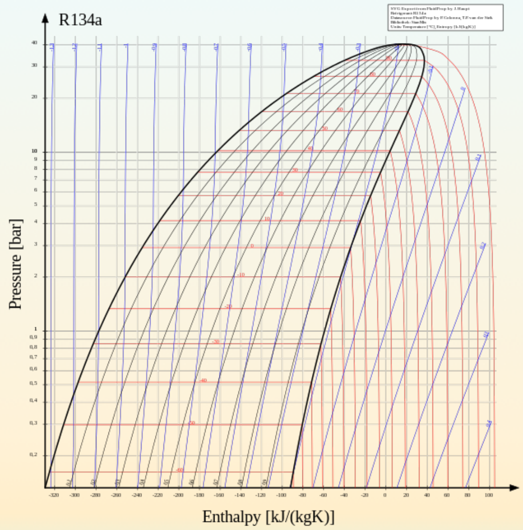

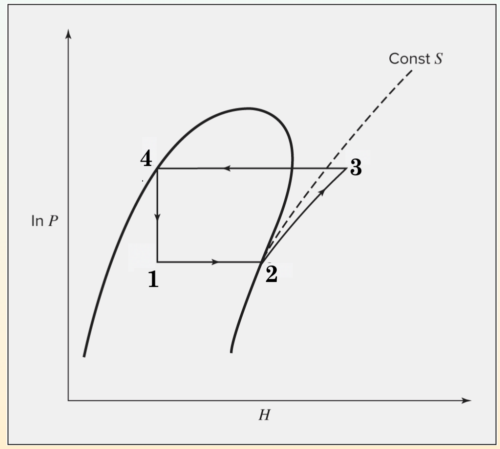

Easy to read $H_2 - H_1$ and $H_3 - H_4$

Property tables at <https://www.ohio.edu/mechanical/thermo/property_tables/R134a/>

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As shown in Sec. 5.2, the efficiency of a Carnot heat engine is independent of the working medium of the engine. Similarly, the coefficient of performance of a Carnot refrigerator is independent of the refrigerant. The irreversibilities inherent in vapor-compression cycles cause the coefficient of performance of practical refrigerators to depend to a limited extent on the refrigerant. Nevertheless, such characteristics as toxicity, flammability, cost, corrosion properties, global warming potential, ozone depletion potential, and vapor pressure are of greater importance in the choice of refrigerant. Safety and environmental concerns strongly constrain the range of compounds that can be considered for use as refrigerants. So that air cannot leak into the refrigeration system, the vapor pressure of the refrigerant at the evaporator temperature should be greater than atmospheric pressure. On the other hand, the vapor pressure at the condenser temperature should not be unduly high because of the initial cost and operating expense of high-pressure equipment. These many requirements limit the choice of refrigerants to relatively few fluids.

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Ammonia, methyl chloride, carbon dioxide, propane, and other hydrocarbons can serve as refrigerants, particularly in industrial applications. Halogenated hydrocarbons came into common use as refrigerants in the 1930s. Fully halogenated chlorofluorocarbons were the most common refrigerants for several decades. However, these stable molecules were found to persist in the atmosphere for many years, allowing them to reach the stratosphere before finally decomposing by reactions that severely deplete stratospheric ozone. As a result, their production and use is now banned. Certain less-than-fully halogenated hydrocarbons, which cause relatively little ozone depletion, and hydrofluorocarbons that cause no ozone depletion now serve as replacements in many applications. A primary example is 1,1,1,2-tetrafluoroethane (HFC-134a).[3] Unfortunately, these refrigerants have extremely high global warming potentials, hundreds to thousands of times greater than CO_2, and for that reason are now being banned in many countries. New hydrofluorocarbon refrigerants with lower global warming potential, such as 2,3,3,3-tetrafluoropropene (HFO-1234yf), are beginning to replace first-generation hydrofluorocarbon refrigerants such as R134a.

See Wikipedia List of refrigerants for Atmospheric Lifetime, Ozone Depletion Potential, Global Warming Potential, and Occupational Exposure Limits

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Refrigeration is often rated in tons

1 ton = Freeze 1 ton of H_2O/day.

= 12,000 Btu/h = 12,661 kJ/h

The Seasonal Energy Efficiency Rating (SEER) is calculated as

$$\text{SEER} = \frac{\text{BTU/hr of cooling}}{\text{Watt of power}} = \frac{0.2931\ \text{W}}{\text{W}}$$

$$\text{COP} = \omega = \frac{\text{W}}{\text{W}} = 3.412\frac{\text{Btu/h}}{\text{W}}$$

$$\text{SEER} \approx 3.4\ \text{COP}$$

3 Ton, 14 to 16 SEER Condenser, R-410A Refrigerant, Northern Sales Only

Mouse over or pinch image to zoom in

★★★★★ (258 Reviews)

Model: BLUERIDGE BA16L36P

- ✓ Designed for easy installation and maintenance
- ✓ Reliable and consistent cooling power
- ✓ Worry free and energy efficient performance
- ✓ Peace of mind with 10 year warranty

$1,420.00

Or as low as $89/mo. Details

You save: 28%

Compare to: ~~$1,985.00~~

Volume Discounts

Qty: 1

Add to Cart

✓ In Stock and Ready to Ship

If ordered by 1PM CST M-F, ships same day. All items on your order must be in stock for same-day shipping.

Includes

Free Shipping | Easy Returns

Premium Guarantee | Ten Year Warranty

Free Video

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Analyze 3 ton, 14 to 16 SEER, Refrigerant R401A

$$3 \text{ ton} = 3 \cdot 12{,}000 \text{ Btu/h} = 36{,}000 \text{ Btu/h} = 10.55 \text{ kW}$$

$$\text{SEER} \approx 3.4 \text{ COP}$$

$$\omega = \frac{\text{SEER}}{3.4} = 4.1 \text{ to } 4.7$$

Refrigerant R401A is a HCFC blend of R-22 ($CHClF_2$), R-152A ($C_2H_4F_2$), and R-124 (C_2HClF_4). It is designed as a replacement for R-12 (CCl_2F_2). AL = 8.5 years, ODP = 0.034, GWP = 1,182, OEL = 1,000 ppm.

For comparison R-12: AL = 100 years, ODP = 1.0, GWP = 10,200, OEL = 1,000 ppm.

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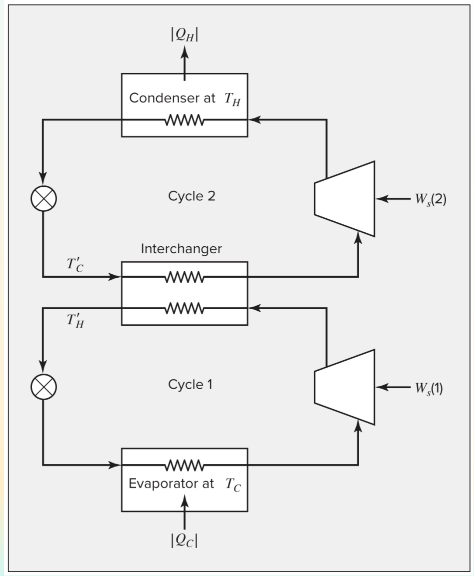
How do you get to low temperatures?

Cascade Cycles

How would you analyze the whole cycle?



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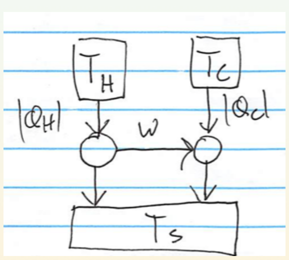
Imagine the following:

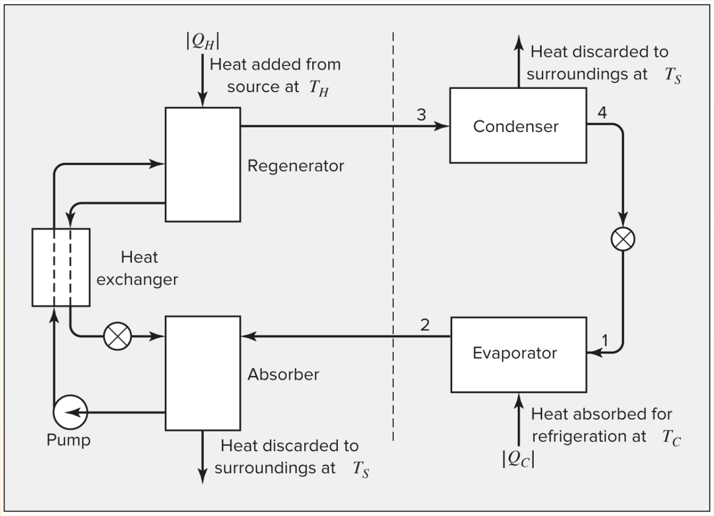


Why would you do this?

If Carnot units

$$|W| = 1 - \frac{T_S}{T_H}\left|Q_H\right| = \frac{T_S - T_C}{T_C}\left|Q_C\right|$$

$$\frac{\left|Q_C\right|}{\left|Q_H\right|} = \frac{T_H - T_S}{T_H}\frac{T_C}{T_S - T_C} = \frac{T_C}{T_H}\frac{T_H - T_S}{T_S - T_C}$$



Typical fluids:

- Ammonia – water
- Water – lithium bromide

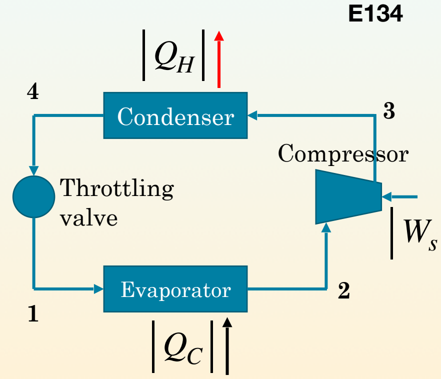
What would you need to analyze?

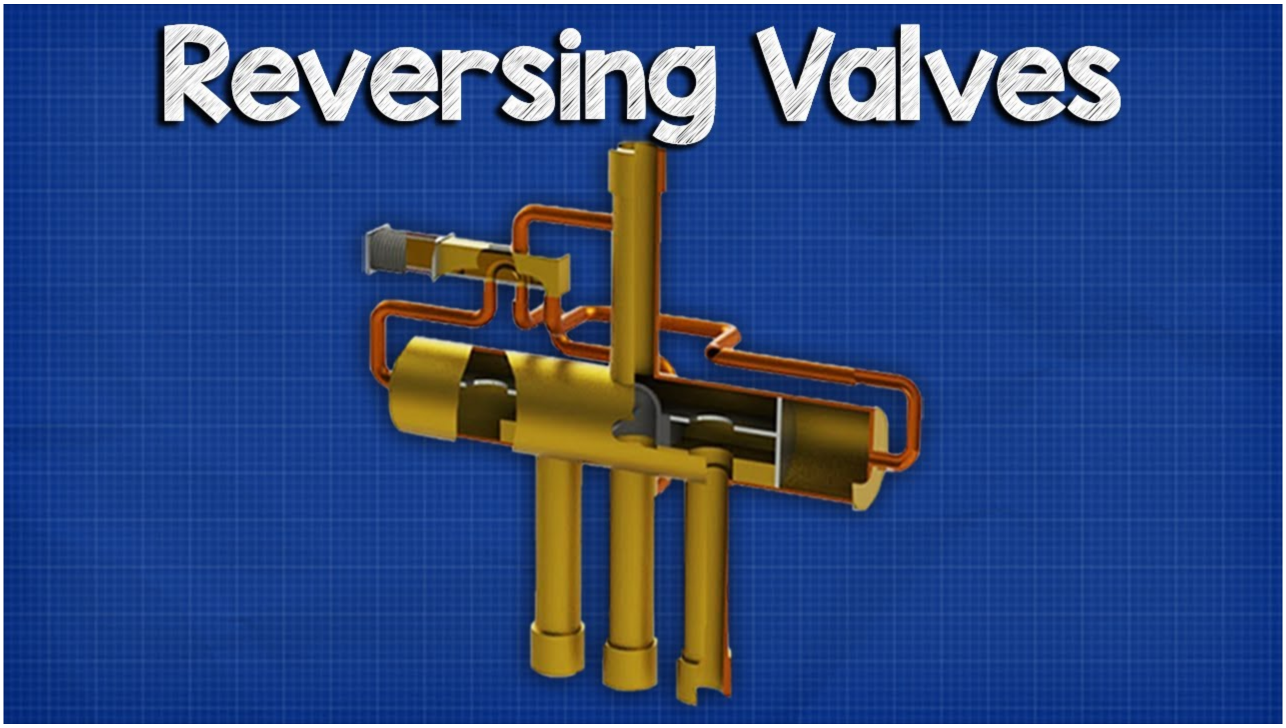
The Heat Pump for Home Heating

As mentioned above, in the heat pump, you want to generate Q_H to heat the home, and extract Q_C from the cold ambient.

$$\omega = \frac{|Q_H|}{|W|} = \frac{H_3 - H_4}{H_3 - H_2}$$

With a combo air conditioner and heat pump how would you switch from AC to heat pump and back?




Reversing Valves