47201 Engineering thermodynamics

Lecture 8b: Vapor refrigeration cycles (Ch. 9.4)

Carnot limitations

As with the Carnot power cycle, there are practical limitations of the Carnot cycle. The main practical limitations of the Carnot cooling cycle are:

1. The compressor failure rate goes up dramatically when it has to compress a mixture of gas and liquid droplets.

2. The expander is expensive and does not produce very much work

The (ideal) vapor compression (reverse Rankine) cycle

Similar to the Rankine cycle, the vapor compression cycle modifies the Carnot cycle to make components more practical. The cycle consists of

1. Two phase fluid enters the evaporator and absorbs heat until it reaches a saturated vapor.
2. The vapor is then compressed isentropically to the high pressure (condenser pressure) where it is a superheated vapor
3. Heat is rejected from the high pressure fluid in the condenser until it reaches a saturated liquid.
4. The liquid goes through an expansion valve where no work is extracted. This is modelled as a constant enthalpy process.

The vapor compression (reverse Rankine) cycle

$$COP = \frac{\dot{Q}_C}{\dot{W}_{comp}} \quad \text{Eq. (9.27)}$$

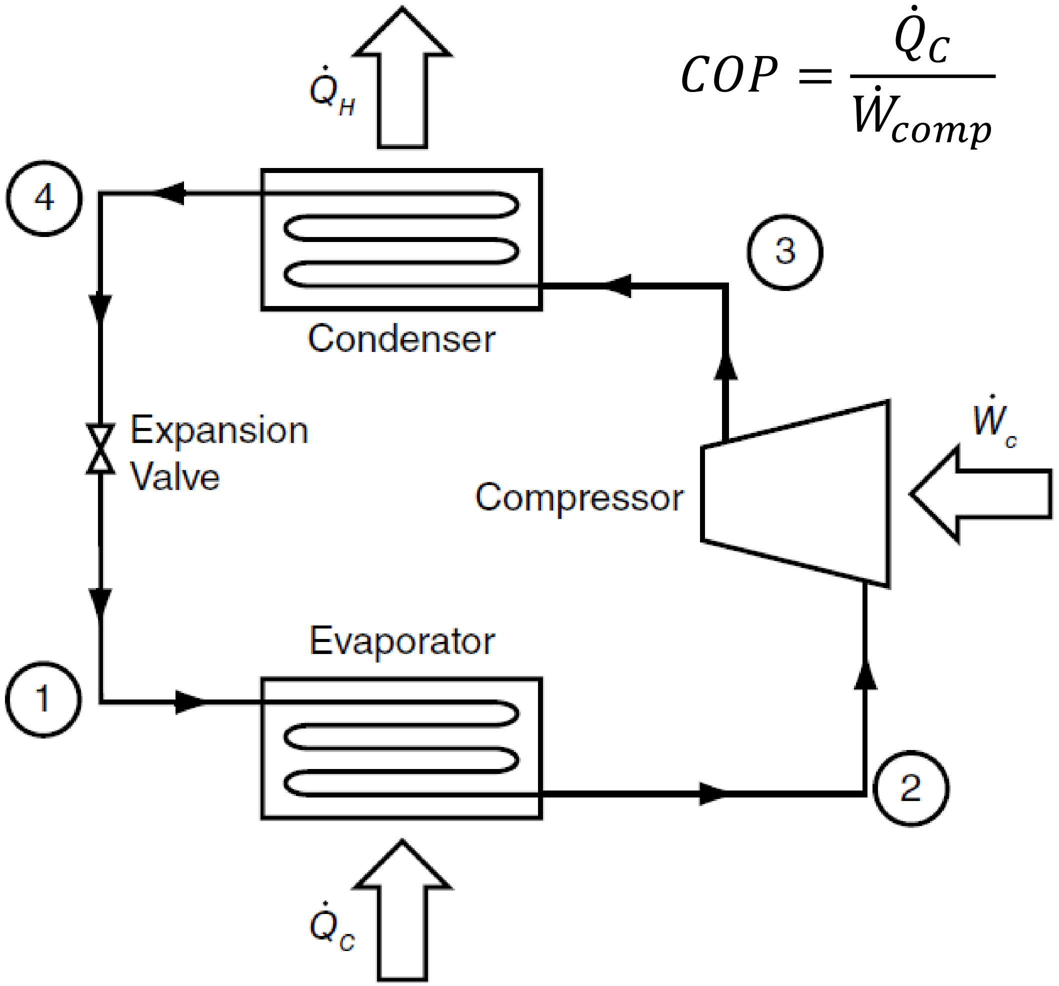


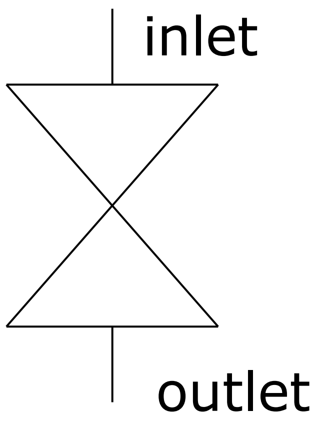
Figure 9.11 Vapour refrigeration cycle.

Analyzing the vapor compression cycle

The approach is similar to analyzing power cycles. Start from a known state and analyze individual components to determine subsequent states. A suggested approach is:

1. Typically, the inlet to the compressor or the inlet to the expansion valve is known.
   - Inlet to the compressor is saturated vapor at the evaporator pressure, inlet to the expansion valve is saturated liquid at the condenser pressure.
2. Model compression as isentropic unless a compressor efficiency is given.
3. Expansion across the valve is isenthalpic (see next slide).
4. Main outputs are cooling at the evaporator and work input to the compressor

Expansion valve



The expansion valve is generally modelled as isenthalpic

$$h_i = h_o$$

Example: Calculate the difference in quality of fluid exiting the isenthalpic valve compared to an isentropic expansion. The valve operates between pressures of 800 kPa and 200 kPa using R134a as a refrigerant. Saturated liquid enters the valve at 800 kPa.

Solution: Quality exiting the isenthalpic valve is 0.277 while it is 0.255 from the isentropic valve. The increased quality from the isenthalpic valve reduces the possible cooling of the cycle.

Example 9.5

Problem: A freezer working on a reverse Rankine cycle uses refrigerant 134a with a mass flow rate of 0.10 kg / s. The refrigerant leaves the evaporator as saturated vapour at a temperature of –8 °C. It leaves the condenser as saturated liquid at a pressure of 0.8 MPa.

Find: Power required to drive the compressor, coefficient of performance of refrigeration *COP* of the Rankine cycle, the coefficient of performance of refrigeration *COP* of a Carnot cycle operating between the same temperatures.

Note: the book calculates the COP of the vapor compression cycle incorrectly. h_2 and h_3 get mixed up.

Assumptions:

1. Steady state
2. Isentropic compression
3. Isenthalpic expansion

Example 9.5 solution strategy

Draw the T-s diagram

- Start from state 2 where the properties are fully defined (saturated vapor at the lower pressure)
- Find state 3 using the fact that compression is isentropic ($s_3 = s_2$)
- State 4 is fully defined (saturated liquid at the high pressure)
- Find state 1 by know that expansion through the valve is isenthalpic ($h_1 = h_4$)
- Calculate cooling power and work input once all states are known.
- We can use values in Appendix 9 or EES

Example 9.5 finding the compressor outlet

We can look up the state of the compressor inlet (state 2) from Appendix 9a: $h_2 = 242.54 \frac{kJ}{kg}$ and $s_2 = 0.9239 \frac{kJ}{kg\ K}$

- We calculate state 3 by knowing that $s_3 = s_2 = 0.9239 \frac{kJ}{kg\ K}$. However, state 3 is a superheated vapor so we need to use Appendix 9c.
- We can interpolate the enthalpy directly using the entropy. So from Appendix 9c, at 0.8 MPa and T=31.33 C, $s = 0.9066 \frac{kJ}{kg\ K}, h = 264.15 \frac{kJ}{kg}$ and at 0.8 MPa and T = 40 C, $s = 0.9374 \frac{kJ}{kg\ K}, h = 273.66 \frac{kJ}{kg}$
- We then interpolate to find that $h_3 = 269.49 \frac{kJ}{kg}$

Refrigerants

In contrast to power production equipment, refrigerants used in cooling cycles are constantly changing for practical and regulatory reasons

- Many refrigerants have ozone depleting potential or a high global warming potential when they leak out of the system.
  - Ozone depleting refrigerants (primarily CFCs) have been phased out. This is the Montreal protocol.
  - Refrigerants with high global warming potential are being phased out (HFCs). This is the Paris Agreement.

- Refrigerents also have a number of practical requirements, such as having a positive gage pressure in the evaporator, critical temperature, chemical compatibility etc.

- There are a large number of available refrigerants and many are available in EES

Refrigerant naming

R $\boxed{x}\boxed{y}\boxed{z}$

fluorine atoms

hydrogen atoms + 1

carbon atoms - 1

All remaining atoms are chlorine

For example R12 (Freon) has one carbon atom, no hydrogen atoms, 2 fluorine and then two chlorine atoms (technically R012). R12 is a chlorofluorocarbon, CFC

Designations such as ”a” refer to different molecular structures of the same elements

Some videos about refrigeration cycles/systems

https://www.youtube.com/watch?v=L5jQqmaFKOE

https://www.youtube.com/watch?v=1Hva1PLCYUA

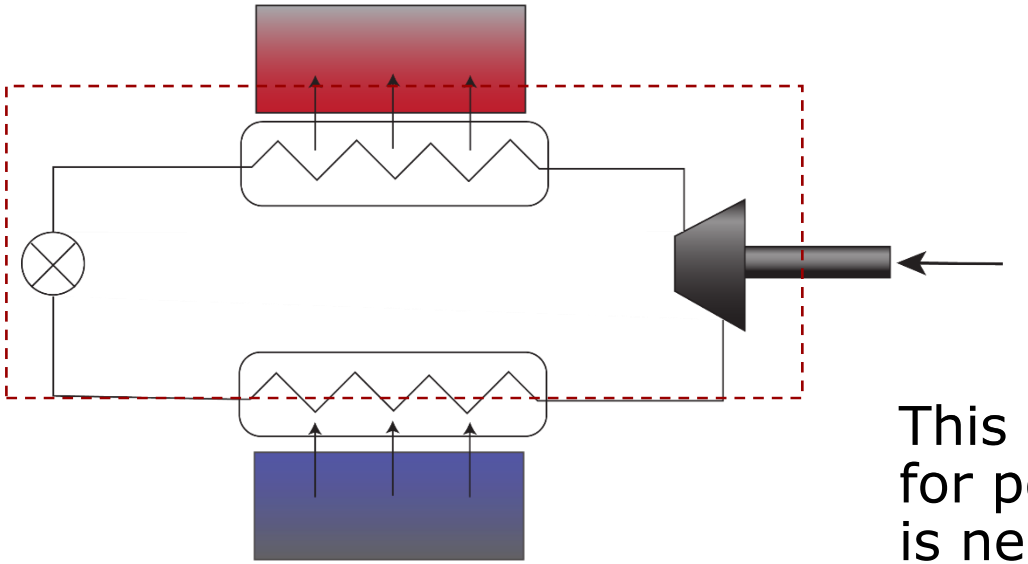
Analyzing vapor compression with isentropic efficiencies

- Just as we analyzed turbines with isentropic efficiencies, the compressor in a vapor compression cycle can also have an isentropic efficiency

$$\eta_{comp} = \frac{h_{o,s} - h_i}{h_o - h_i} \qquad \text{Eq. (6.86)}$$

1st law analysis of vapor compression cycles

System has two inputs (heat at the cold end and work into the compressor and one output (heat rejected from the cold end)



$$\dot{Q}_C + \dot{W}_{comp} = \dot{Q}_H$$

$$\dot{W}_{comp} = \dot{Q}_H - \dot{Q}_C$$

This energy balance is the same for power cycles, but the power is negative

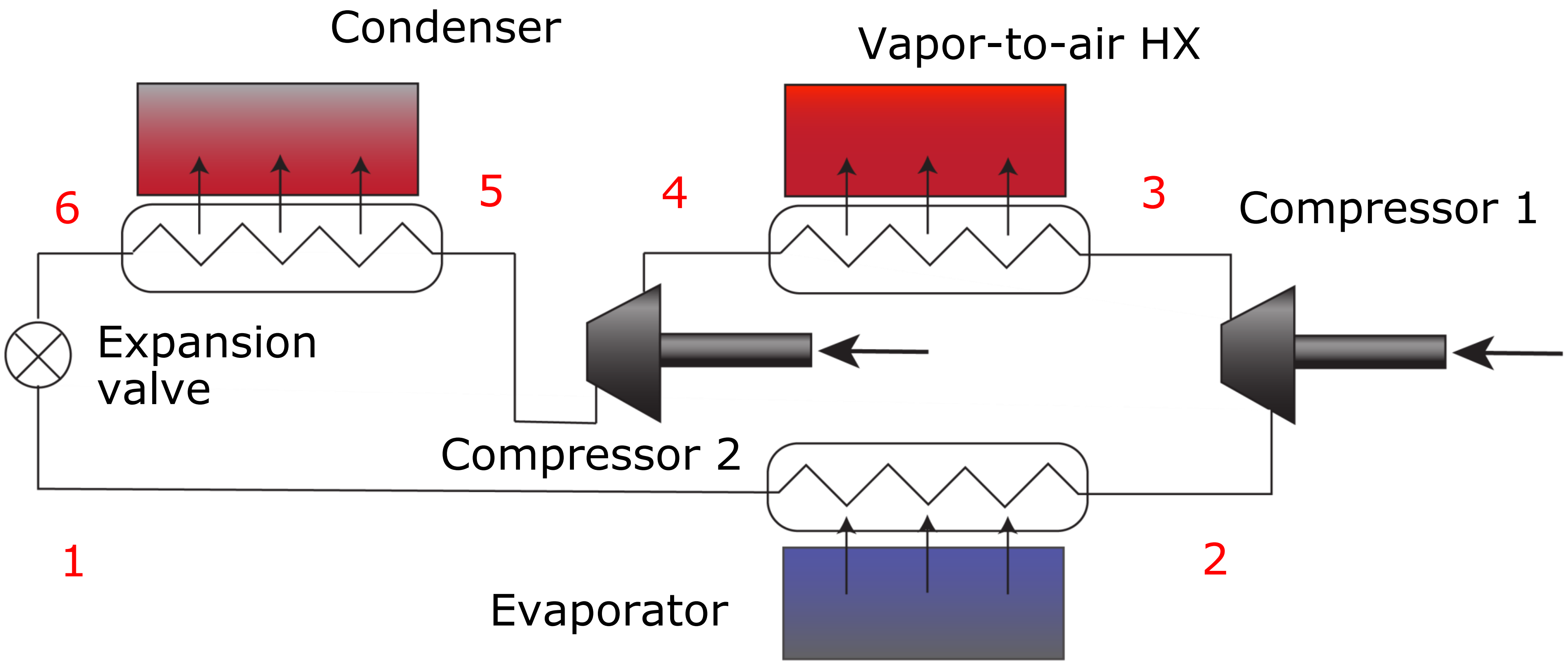
Advanced vapor compression configurations

Just as the Rankine cycle has been modified to improve efficiency, reliability and power density, the vapor compression cycle also has several modifications. We will look at:

- The intercooled cycle. This concept is analogous to the superheat and reheat concept
- Cascaded cycle. Using cascaded vapor compression cycles can increase the overall temperature span

Intercooled cycle

- The intercooled cycle uses a two-stage compression to reduce superheat



Intercooled cycle efficiency

- The only modification to the COP is that the work from both compressors must be included.

For an intercooled cycle

$$COP = \frac{\dot{Q}_C}{\dot{W}_{comp1} + \dot{W}_{comp2}}$$

Intercooled cycle example

Start from example 9.5: A freezer working on a reverse Rankine cycle uses refrigerant 134a with a mass flow rate of 0.10 kg / s. The refrigerant leaves the evaporator as saturated vapour at a temperature of –8 °C. It leaves the condenser as saturated liquid at a pressure of 0.8 MPa.

Add: a second stage compressor with an inlet pressure of 0.45 MPa (the condenser pressure remains at 0.8 MPa). The intercooler cools the vapor back to saturated vapor before it enters the high pressure compressor.

Find: Power required to drive the two compressors and coefficient of performance of refrigeration *COP* of the Rankine cycle.

From example 9.5, the COP is 5.548

Example 9.5 intercooled solution strategy

Draw the T-s diagram

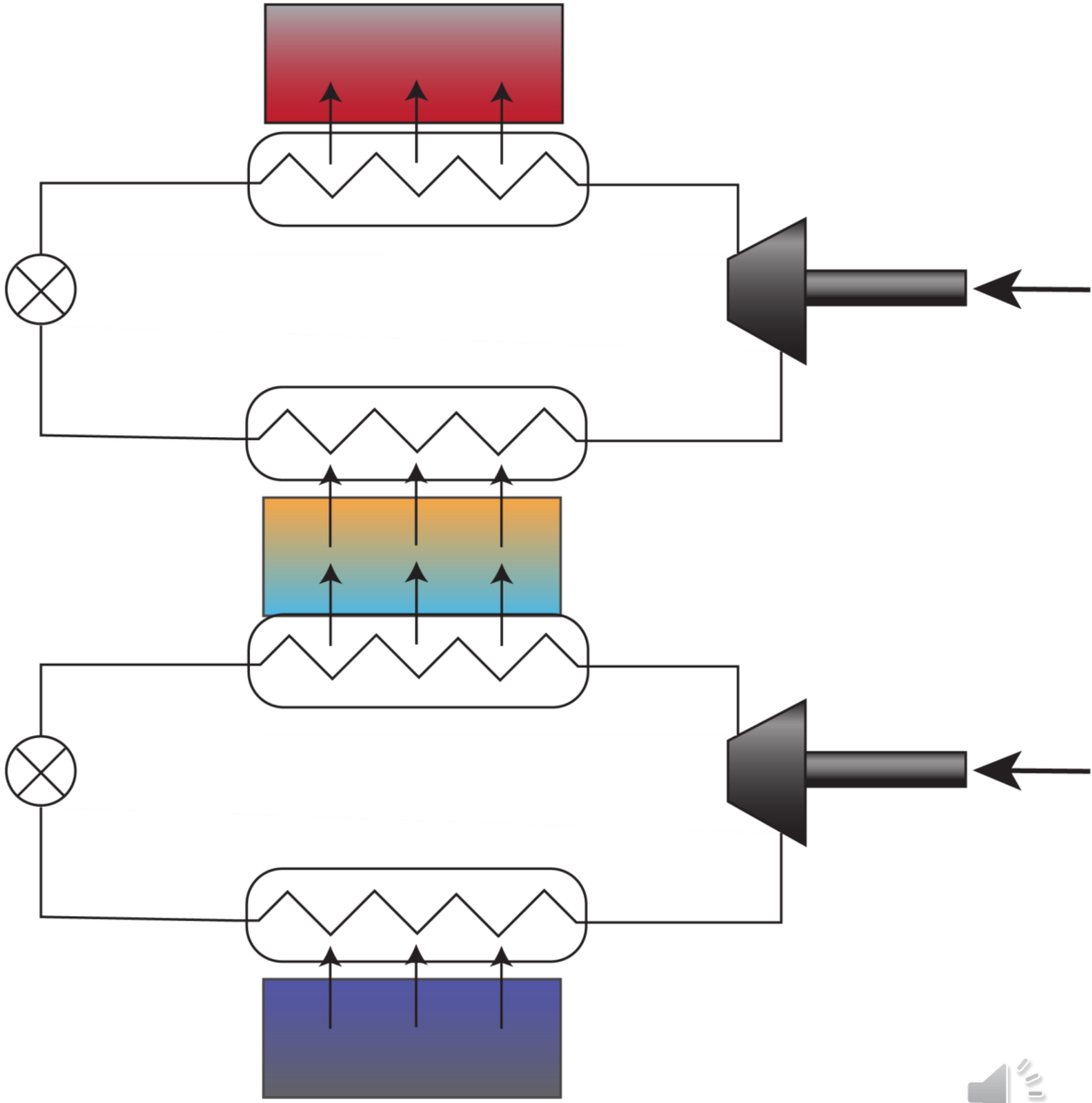
- Start from state 2 where the properties are fully defined (saturated vapor at the lower pressure)
- Find state 3 using the fact that compression is isentropic ($s_3 = s_2$)
- State 4 is saturated vapor at the intermediate pressure
- Find state 5 and 6 the same way as 3 and 4.
- Find state 1 by know that expansion through the valve is isenthalpic ($h_1 = h_4$)
- Calculate cooling power and work input once all states are known.

Cascaded cycle

- The cascaded cycle consists of two independent vapor compression systems coupled at the evaporator of the high temperature cycle to the condenser of the low temperature cycle.

- The two cycles are completely independent, meaning they can operate at different pressures, using different refrigerants and can have different configurations.

- The one constraint is that the heat rejected from the low temperature cycle must match the cooling power of the high temperature cycle.



Cascaded cycle analysis

- We can call the cooling power absorbed by the low temeprature cycle $\dot{Q}_{C,Lo}$, the compressor work for the low temperature cycle is $\dot{W}_{comp,Lo}$ and the compressor work for the high temperature cycle is $\dot{W}_{comp,Hi}$

- The desired output is the cooling at the low temperature reservoir so the cycle COP is:

$$COP = \frac{\dot{Q}_{c,Lo}}{\dot{W}_{comp,Lo} + \dot{W}_{comp,Hi}}$$

- With the constraint that

$$\dot{Q}_{H,Lo} = \dot{Q}_{c,Hi}$$

Example: heat pump for domestic hot water

Given: domestic hot water must be heated to 60 C in an area where temperatures can be expected to go as low as -20 C. A two stage cascaded heat pump is used, where the cold cycle evaporator operates at -20 C and the hot side condenser operates at 60 C. Both cycles use R134a as the working fluid. The hot side of the cold cycle and the cold side of the hot cycle both operate at 20 C. The heating power to the water is 600 W.

Find: (a) the refrigerant flow rate in each cycle and (b) the COP of the hot water heater.

Example: heat pump for domestic hot water

1. Define the states
2. Start from the high temp cycle (because heating power there is defined)
3. Work all the way around the cycle to define all states
4. Find total work input and efficiency