47201 Engineering thermodynamics

Lecture 8a: Ideal refrigeration and heat pump cycles (Ch. 8.4-5)

Clarification on the Rankine cycle

A pump operating with an incompressible fluid (as we assume in our Rankine cycle analysis) does not operate isentropically. So $s_o \neq s_i$ for a pump.

- The enthalpy at the pump outlet will be higher than at the inlet, according to $\mathrm{h_o} = h_i + v(P_o - P_i)$

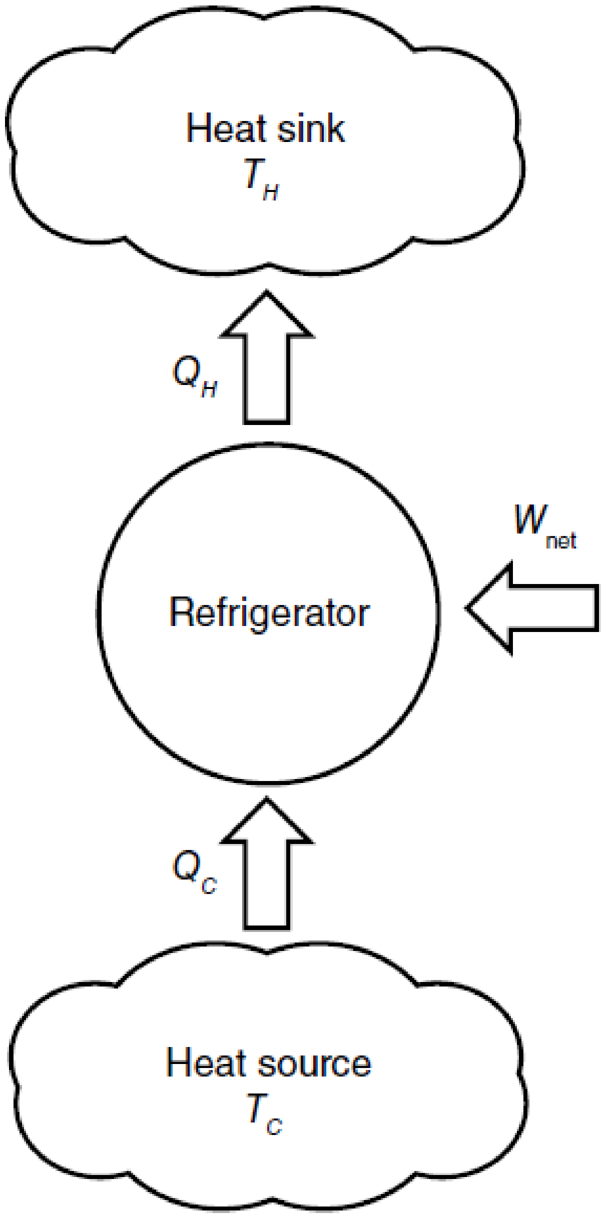
- Since the pump operates with a subcooled liquid, the increase in enthalpy through the pump will correspond to an increase in temperature, and a corresponding increase in entropy. So the entropy will increase across the pump.

Refrigerators

We can also run the heat engine ”backwards” by adding work rather than generating it. The system then becomes a refrigerator

- The energy balance for the system is exactly the same as for a heat engine, but the signs of all the terms are flipped. We typically rearrange to give the energy balance in terms of cooling power

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



Efficiency of a cooling cycle

For a cooling cycle, the desired output is heat absorption at the cold end and the input is electricity. The ratio of the two is the coefficient of performance, *COP*

$$COP = \frac{\text{heat absorbed at the cold end}}{work\ input} = \frac{Q_C}{W_{net}}$$

- We can also define the *COP* on a rate basis

$$COP = \frac{\dot{Q}_C}{\dot{W}_{net}}$$

A note on mass balance in power and refrigeration cycles

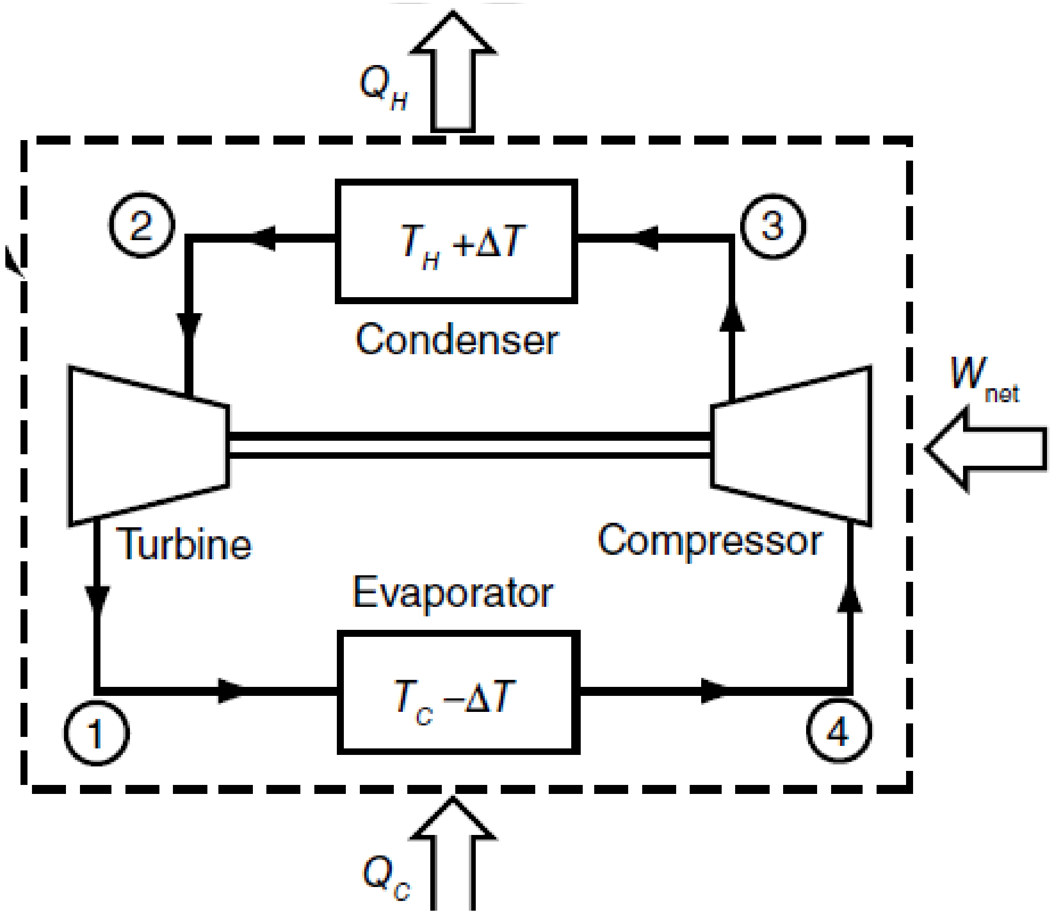
For the cycles that we will study in this course, each component has a single inlet and outlet and operates at steady state. Therefore, the mass balance is straightforward, with the same mass flow rate in and out of each component.

Carnot refrigeration cycle

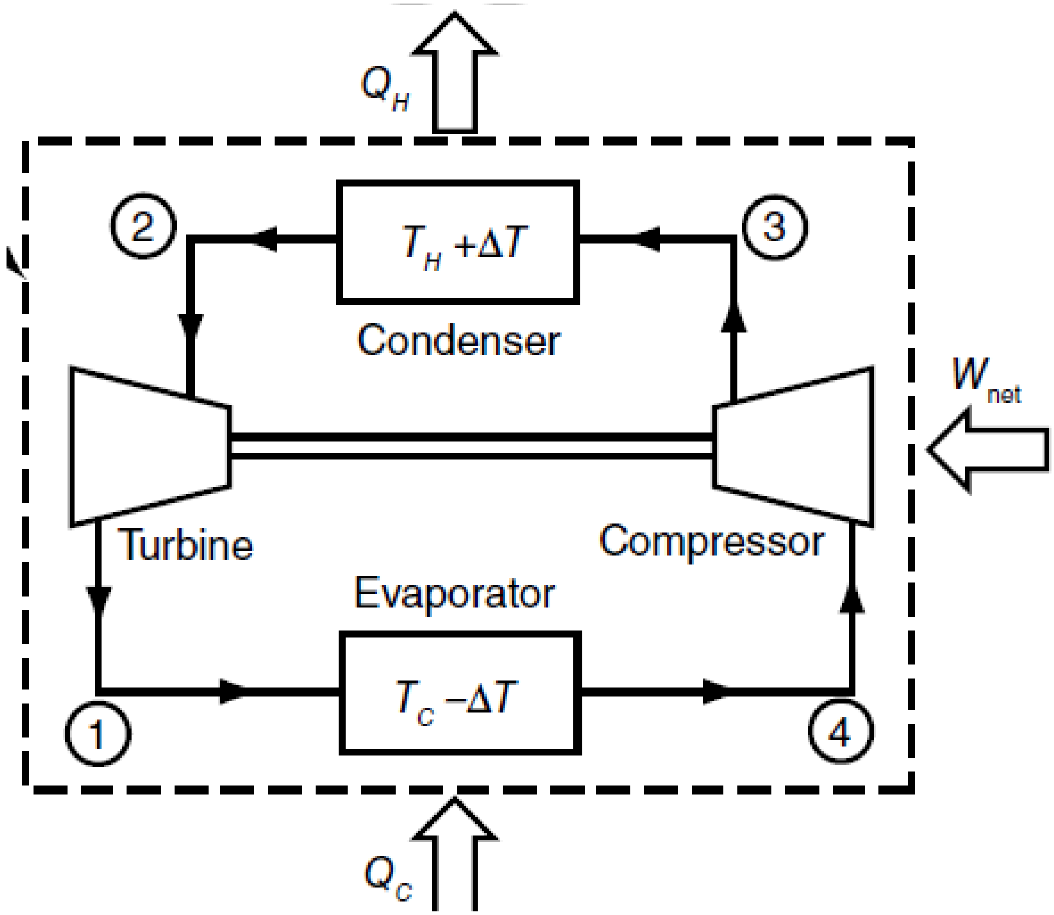
The two-phase Carnot cycle can operate in cooling mode where electricity is input to the system and the goal is to cool a load at the evaporator.

The cycle consists of:

1. Isentropic compression of a two phase fluid
2. Isothermal heat transfer to a hot reservoir
3. Expansion of the two-phase fluid to extract work
4. Isothermal heat transfer from the cold reservoir



Carnot refrigeration cycle T-s diagram



Efficiency of the Carnot refrigeration cycle

The Carnot cycle represents the most efficient cooling cycle between to thermal reservoirs. The efficiency is defined as the amount of heat accepted from the cold reservoir over the work input. This efficiency can be greater than 1 and is called the coefficient of performance (COP)

$$COP_{Carnot} = \frac{Q_C}{W_{comp} - W_{ex}} = \frac{T_C}{T_H - T_C} \text{ or } \frac{1}{{T_H}/{T_C} - 1}$$

Example 8.5

- **Problem:** A Carnot refrigerator using 0.005 kg / s of refrigerant 134a has a condenser pressure of 700 kPa and requires 500 W to operate. What is the rate at which it cools the low temperature region?.
- **Assumptions:**

1. Carnot cycle (isentropic expansion and compression)
2. Steady state

Example 8.5 solution

- We know the properties at states 2 and 3 because they are defined by the Carnot cycle. State 2 is a saturated liquid and state 3 is a saturated vapor and both are at the condenser pressure (high pressure). So, using values from Appendix 9b, the heat rejected at the condenser can be calculated as

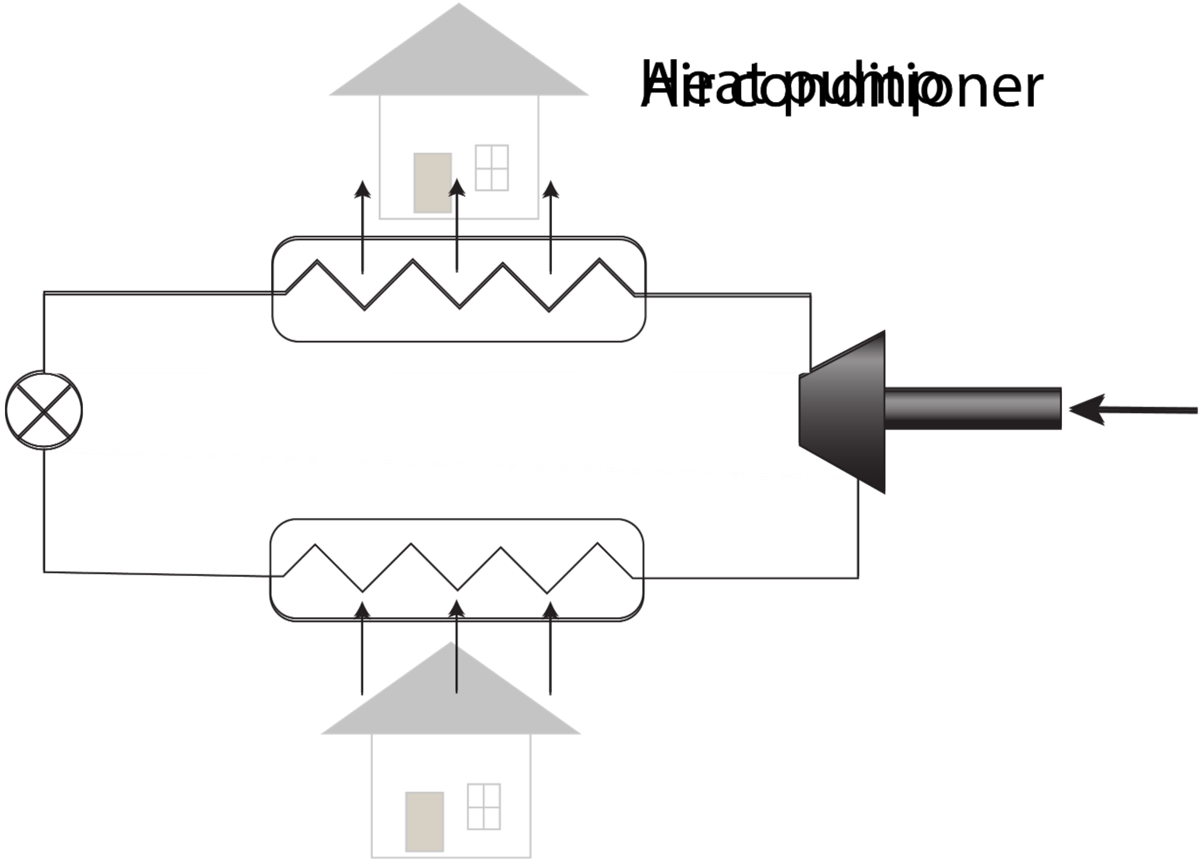
$$\dot{Q}_H = \dot{m}(h_2 - h_3) = 0.005\frac{kg}{s}\left(261.85\frac{kJ}{kg} - 86.78\frac{kJ}{kg}\right) = 0.875\ kW$$

- Then the heat aborbed at the cold end can be calculated from the energy balance of the cycle

$$\dot{Q}_C = \dot{Q}_H - \dot{W}_{net} = 0.875\ kW\ - 0.5\ kW = 0.375\ kW$$

Heat pumps

- A heat pump is a type of refrigeration cycle. The difference between a refrigeration cycle and a heat pump is that the goal of a heat pump is to provide heat from the condenser.



Why a heat pump

Electric heaters are cheap, compact and can approach 100% efficiency. Why would anyone build a heat pump?

Electric heaters can achieve near 100% efficiency, but the heat we get from an electric heater would be the same power that we provide to the compressor in a heat pump.

Going the energy balance of a refrigeration cycle, the heat that we would get from a heat pump is the work to the compressor plus the heat absorbed in the evaporator

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

Heat pump COP

For a refrigeration cycle, the COP is

$$COP_{cool} = \frac{\dot{Q}_c}{\dot{W}_{comp}}$$

For a heat pump, the COP is based on the heat it provides

$$COP_{HP} = \frac{\dot{Q}_H}{\dot{W}_{comp}}$$

Substituting $the\ fact\ that\ \dot{Q}_H = \dot{Q}_C + \dot{W}_{comp}$

$$COP_{HP} = \frac{\dot{Q}_C + \dot{W}_{comp}}{\dot{W}_{comp}} = COP_{COOL} + 1$$

Heat pump Carnot cycle COP

The maximum COP of a heat pump operating between two temperature reservoirs is

$$COP_{HP,Carnot} = \frac{T_H}{T_H - T_C}$$

Heat pump analysis

- Analyzing a heat pump is the same as a cooling cycle. The COP definition is different but calculating all the states is the same.

- Although the cycle is the same, the operating conditions and output levels can be quite different. That means that different refrigerants and operating pressures are often used.
  - Operating temperatures will depend on local climate and the application.