Lecture 36 – Heat pumps

Purdue ME 200, Thermodynamics I

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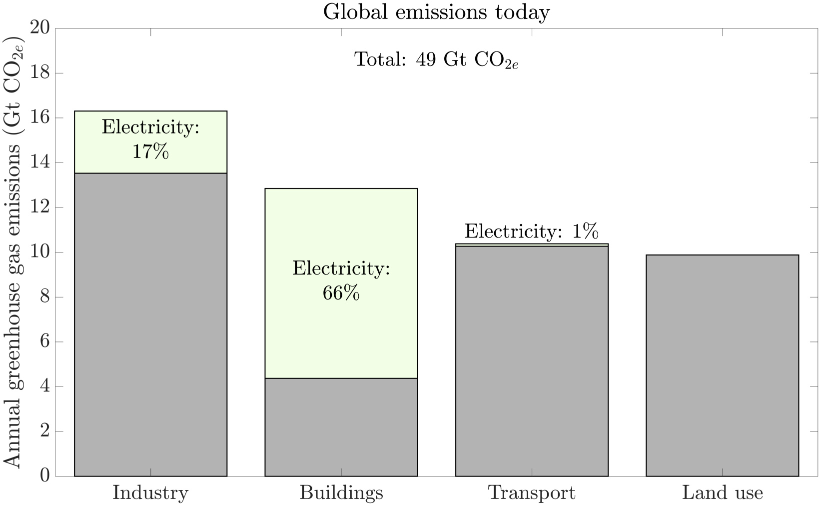
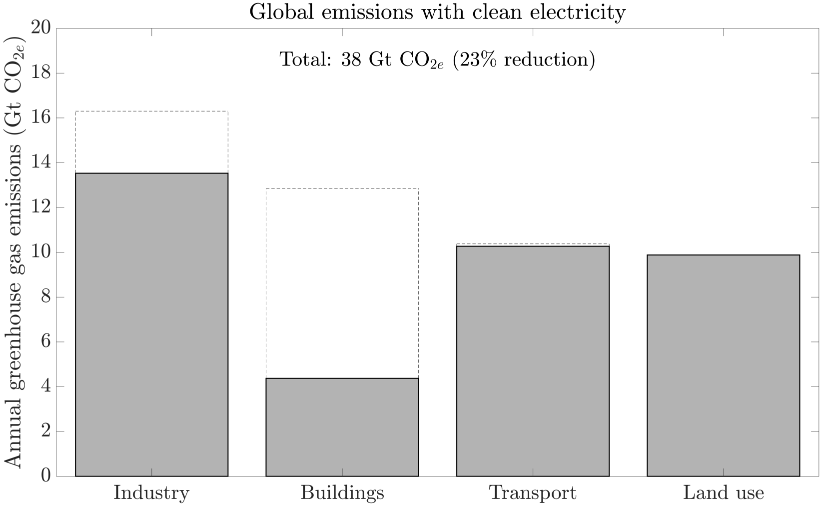
Outline

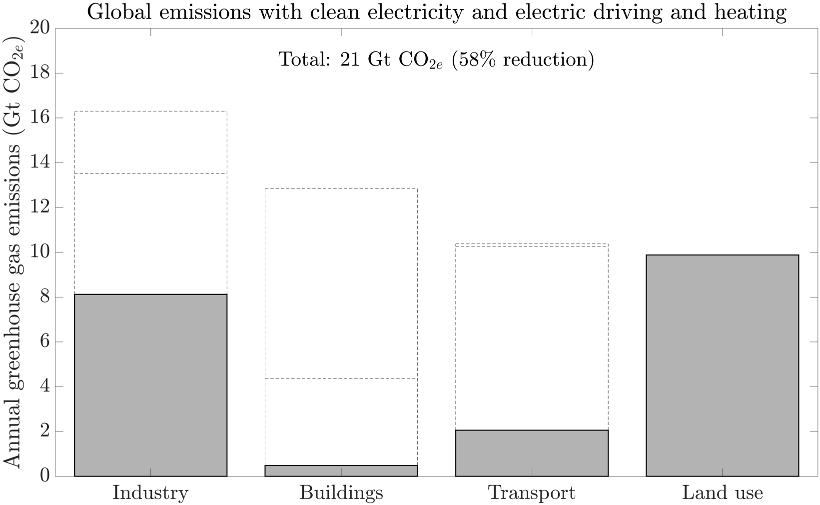
Energy and heat pumps

Vapor-compression heat pumps

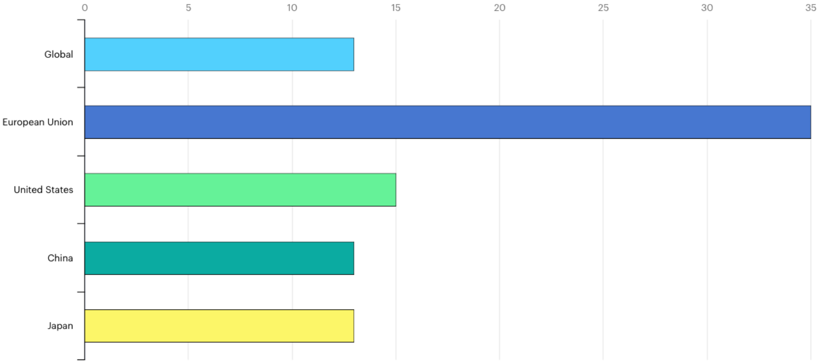
Example


Global emissions today
Total: 49 Gt CO_{2e}
Annual greenhouse gas emissions (Gt CO_{2e})
0
2
4
6
8
10
12
14
16
18
20
Electricity: 17%
Electricity: 66%
Electricity: 1%
Industry
Buildings
Transport
Land use

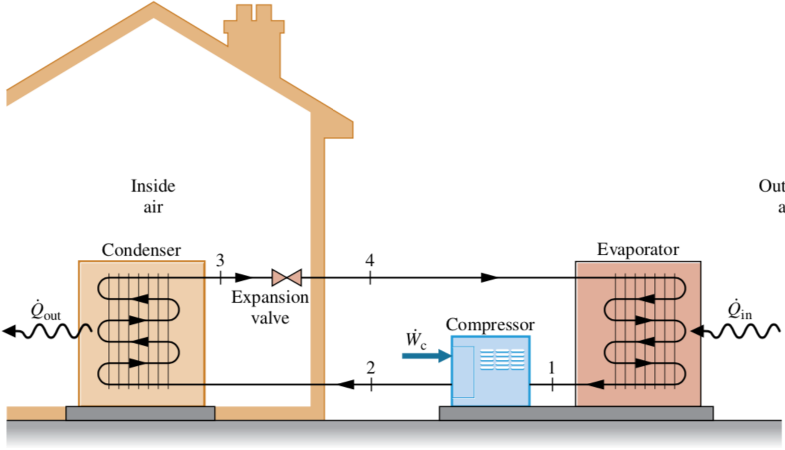

Global emissions with clean electricity
Total: 38 Gt CO_{2e} (23% reduction)
Annual greenhouse gas emissions (Gt CO_{2e})
0
2
4
6
8
10
12
14
16
18
20
Industry
Buildings
Transport
Land use


Global emissions with clean electricity and electric driving and heating
Total: 21 Gt CO_{2e} (58% reduction)
Annual greenhouse gas emissions (Gt CO_{2e})
0
2
4
6
8
10
12
14
16
18
20
Industry
Buildings
Transport
Land use

Percent increase in heat pump sales in 2021 over 2020



International Energy Agency, *Heat Pumps* (2022)



Moran et al., *Fundamentals of Engineering Thermodynamics* (2018)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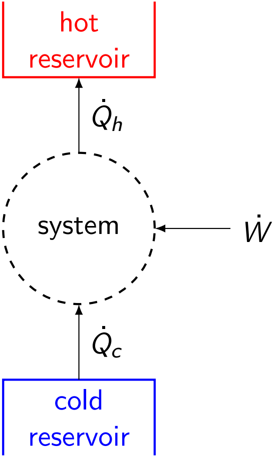
Reminder: heat pump cycles



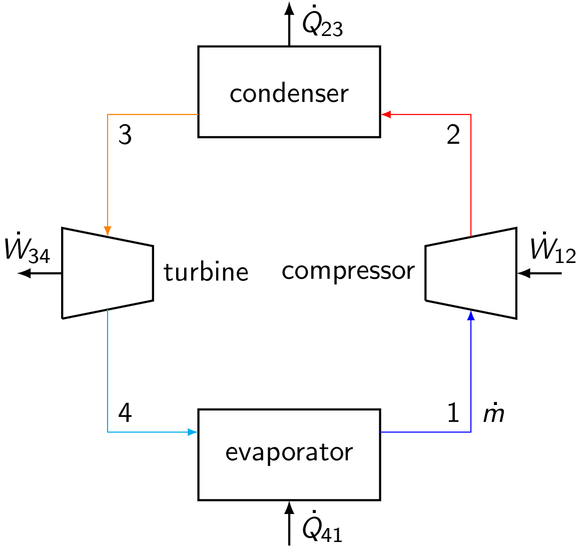
- heating capacity: $\dot{Q}_h$
- coefficient of performance:

$$\gamma = \frac{\text{heat transfer output}}{\text{net work input}} = \frac{\dot{Q}_h}{\dot{W}} = \frac{\dot{Q}_h}{\dot{Q}_h - \dot{Q}_c} = \frac{1}{1 - \dot{Q}_c/\dot{Q}_h}$$

- Carnot performance limit:

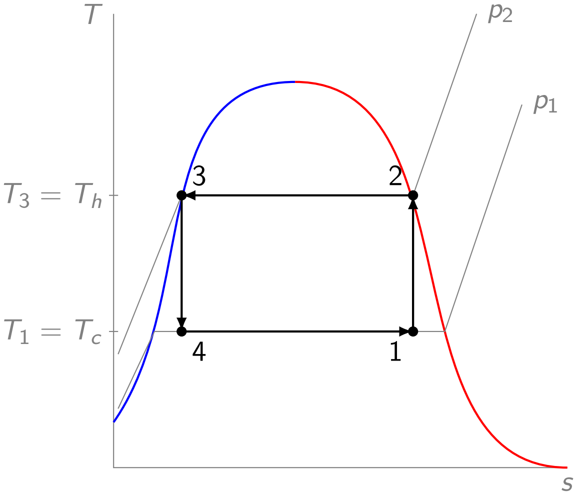
$$\gamma \leq \frac{1}{1 - T_c/T_h}$$

Carnot heat pump cycle schematic



sign convention: energy flows are positive in the arrow directions

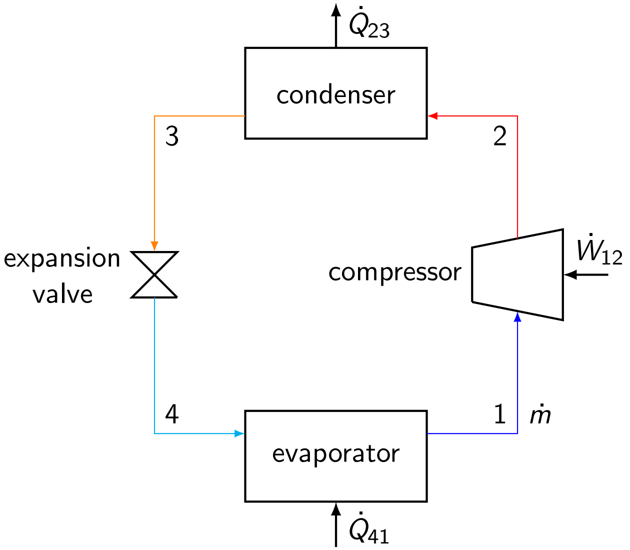
T-s diagram of the Carnot heat pump cycle



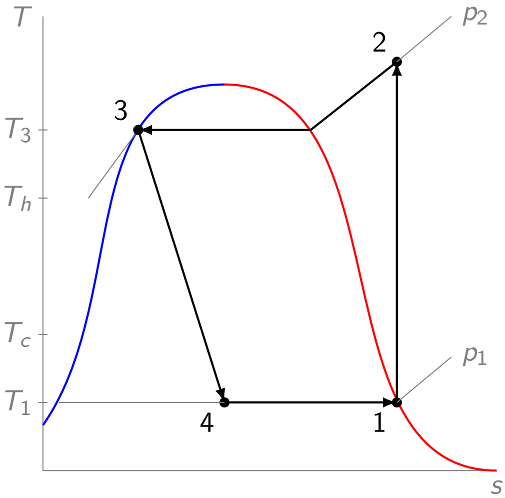
Reminder: the ideal vapor-compression cycle

- the ideal vapor-compression cycle is like the Carnot cycle, but
    - ◇ heat transfers over finite ΔT in the evaporator and condenser
    - ◇ the compressor handles superheated vapor, not SLVM
    - ◇ an expansion valve replaces the turbine
- it's still ideal in that
    - ◇ compression is isentropic
(the compressor is adiabatic and internally reversible)
    - ◇ expansion is isenthalpic
(no stray heat transfer in the expansion valve)
    - ◇ the condenser, evaporator and connecting pipes are isobaric
(no pressure drops due to fluid friction)

Ideal vapor-compression cycle schematic



T-s diagram of the ideal vapor-compression cycle



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Problem statement

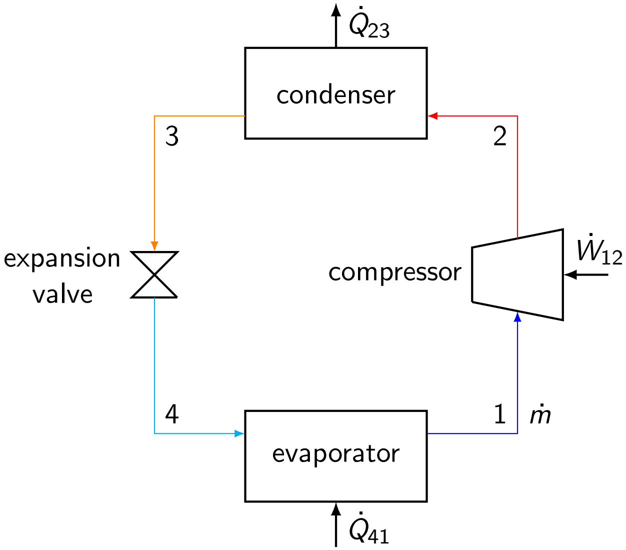
An ideal vapor-compression heat pump circulates 0.085 kg/s of R-134a through isentropic compression (state 1→2), condensation at 10 bar to saturated liquid (2→3), isenthalpic expansion (3→4), and evaporation at 1 bar to saturated vapor (4→1).

(a) Find the temperature, pressure, specific enthalpy, and specific entropy in each state.

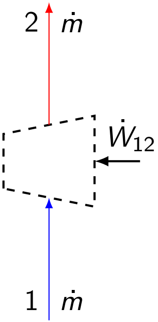
(b) Find the coefficient of performance.

(c) Find the heating capacity and rate of work input.

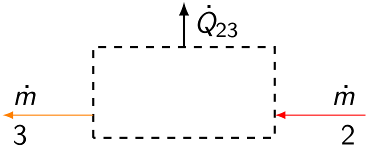
Schematic


$\dot{Q}_{23}$
condenser
3
2
expansion valve
compressor
$\dot{W}_{12}$
4
1
$\dot{m}$
evaporator
$\dot{Q}_{41}$

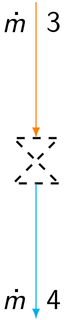
Compressor system diagram



Condenser system diagram



Expansion valve system diagram



Assumptions and basic equations

- **assumptions:**
  - ◇ steady cyclic operation
  - ◇ steady uniform 1D flow
  - ◇ no KE or PE effects
  - ◇ no stray heat transfer
  - ◇ no fluid friction
  - ◇ isentropic compression
  - ◇ isenthalpic expansion
- **basic equations:**
  - ◇ coefficient of performance: $\gamma = \dot{Q}_{23}/\dot{W}_{12}$
  - ◇ compressor 1st law: $\dot{W}_{12} = \dot{m}(h_2 - h_1)$
  - ◇ condenser 1st law: $\dot{Q}_{23} = \dot{m}(h_2 - h_3)$
  - ◇ isenthalpic expansion valve 1st law: $h_4 = h_3$

Solution to part (a): find properties in all states

- straight from the problem statement:

state	phase	p (bar)	T ($^\circ$C)	h (kJ/kg)	s (kJ/kg/K)
1	SV	1			
2	SHV	10			
3	SL	10			
4	SLVM	1			

Solution to part (a): (continued)

- direct look-up in the R-134a saturation table:

state	phase	p (bar)	T ($^\circ$C)	h (kJ/kg)	s (kJ/kg/K)
1	SV	1	-26.4	234.46	0.95188
2	SHV	10			
3	SL	10	39.4	107.35	0.39199
4	SLVM	1	-26.4		

Solution to part (a): (state 4)

- the expansion valve is assumed isenthalpic, so $h_4 = h_3$
- this enables quality and entropy calculation in state 4:

$$x_4 = \frac{h_4 - h_\ell(p_4)}{h_v(p_4) - h_\ell(p_4)} = \cdots = 41.47\%$$

$$s_4 = s_\ell(p_4) + x_4(s_v(p_4) - s_\ell(p_4)) = \cdots = 0.43680\text{kJ/kg/K}$$

state	phase	p (bar)	T (°C)	h (kJ/kg)	s (kJ/kg/K)
1	SV	1	-26.4	234.46	0.95188
2	SHV	10			
3	SL	10	39.4	107.35	0.39199
4	SLVM	1	-26.4	107.35	0.43680

Solution to part (a): (state 2)

- the compressor is assumed isentropic, so $s_2 = s_1$
- superheated vapor table resolves state 2:
  - ◇ at $p_2 = 10$ bar, specific entropy is 0.95255 kJ/kg/K at 50 °C
  - ◇ this is close enough to $s_2 = 0.95188$ to skip interpolation

state	phase	p (bar)	T (°C)	h (kJ/kg)	s (kJ/kg/K)
1	SV	1	-26.4	234.46	0.95188
2	SHV	10	50	282.74	0.95188
3	SL	10	39.4	107.35	0.39199
4	SLVM	1	-26.4	107.35	0.43680

Solution to part (b): find the COP

- the heat pump's coefficient of performance is

$$\gamma = \frac{\dot{Q}_{23}}{\dot{W}_{12}}$$

- from the 1st law, $\dot{Q}_{23} = \dot{m}(h_2 - h_3)$ and $\dot{W}_{12} = \dot{m}(h_2 - h_1)$, so

$$\gamma = \frac{\cancel{\dot{m}}(h_2 - h_3)}{\cancel{\dot{m}}(h_2 - h_1)} = \cdots = 3.64$$

Solution to part (c): find the capacity and input work

- the heat pump's heating capacity is

$$\dot{Q}_{23} = \dot{m}(h_2 - h_3) = \cdots = 14.9\text{kW}$$

- the rate of input work is

$$\dot{W}_{12} = \frac{\dot{Q}_{23}}{\gamma} = \cdots = 4.09\text{kW}$$

- alternatively,

$$\dot{W}_{12} = \dot{m}(h_2 - h_1) = \cdots = 4.09\text{kW}$$