Modeling Thermodynamic Systems

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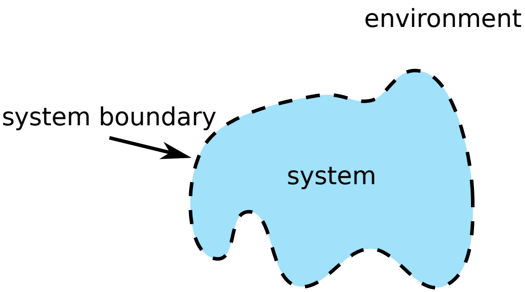
Introduction

Contents

Thermodynamic systems

Thermodynamic system

- Boundary separates system from environment
- Can be open or closed to mass and energy transfer
- homogenoeus/heterogeneous
- State of the system can be described through various properties



Thermodynamic state

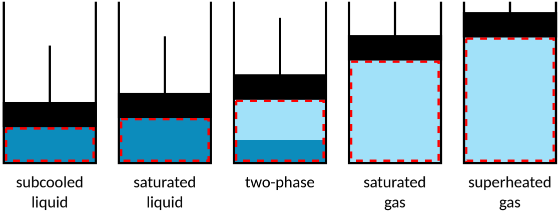
Thermodynamic state

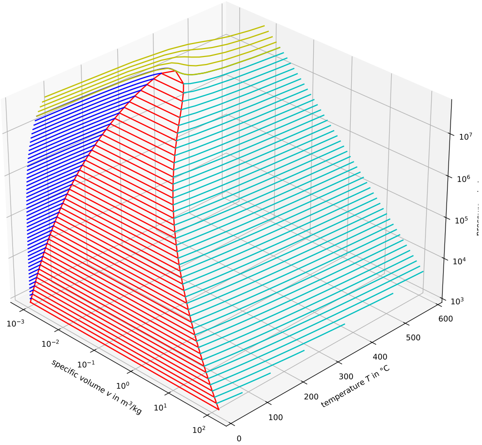
- intensive properties (independant of size of the system)
  - pressure p, unit: $\mathrm{Pa} = \mathrm{N}/\mathrm{m}^2$
  - temperature T, unit: K
- mass specific properties (per kg of mass of the system)
  - specific volume $v = \frac{1}{\rho}$, unit: m^3/kg
  - specific enthalpy h, unit: J/kg
  - specific entropy s, unit: $\mathrm{J}/\mathrm{kg{\cdot}K}$

Phases of fluids

Phases of fluids

- Liquid, two-phase or gaseous
- Isobaric heating leads to evaporation
- Temperature during evaporation is constant





Determining thermodynamic state

Determining thermodynamic state

- Two properties define the state, e.g.
  - pressure and volume
  - temperature and volume
  - pressure and enthalpy
  - pressure and entropy
- pressure and temperature NOT in two-phase region

Exercise

- Calculate the density of R290 at 5 bar and 50 °C.
- What is the enthalpy of saturated liquid ammonia at 75 °C?
- Calculate the vapor mass fraction for the same enthalpy as before but at 25 °C.
- At what pressure does Ammonia start to boil under a pressure of 4 bar?
- What pressure values correspond to saturation temperature of 20 °C, 65 °C and 110 °C for water?
- Calculate the entropy of R134a at saturated gaseous state and a temperature of 10 °C.
- What is the temperature of R134a at the same entropy as previously but twice as much pressure?

Exercise

- Plot saturation pressure vs. saturation temperature for a variety the working fluids ammonia, water, R134a, Pentane, R290, R600, R1233zd(E), in a temperature range from -25 °C to 150 °C.
- Plot the pressure ratio of saturation pressure vs. saturation pressure at 10 °C over a range of temperature from 30 °C to 80 °C.
- Compare the individual lines. What factors might restrict the usage of working fluids in heat pumps?

Thermodynamic processes

Thermodynamic processes

- simplification: open system in steady state operation
- energy balance equation connects
  - outlet o and inlet i states of the fluids with
  - process energy work $\dot{W}$ and heat $\dot{Q}$

$$\dot{Q} + \dot{W} = \sum_{o} \dot{m}_\mathsf{o} \cdot h_o \cdot - \sum_{i} m_i \cdot h_i$$

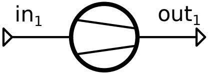
- simplification: single mass flow

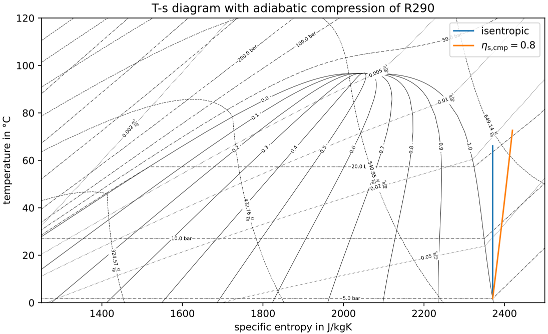
$$\dot{Q} + \dot{W} = \dot{m} \cdot (h_o - h_i)$$

Components: Compressor

Components: Compressor

- Adiabatic to the ambient: $\dot{Q} = 0$
- Energy balance: $\dot{W} = \dot{m} \cdot (h_{\text{out}} - h_{\text{in}})$
- Pressure ratio: $pr = \frac{p_{\text{out}}}{p_{\text{in}}} > 1$
- Isentropic efficiency:
  - $\eta_{\text{s,comp}} = \frac{h_{\text{out,s}} - h_{\text{in}}}{h_{\text{out}} - h_{\text{in}}}$
  - $h_{\text{out,s}} = h\left(p_{\text{out}}, s\left[p_{\text{in}}, h_{\text{in}}\right]\right)$

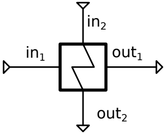


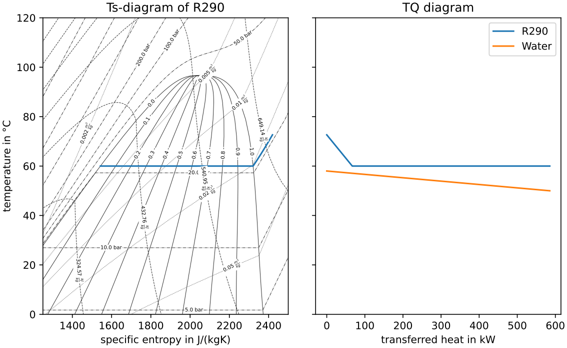


Components: Heat Exchanger

Components: Heat Exchanger

- no transfer of work: $\dot{W} = 0$
- energy balance: $\dot{Q} = \dot{m} \cdot (h_{\text{out}} - h_{\text{in}})$
- pressure losses neglected: $p_{\text{out}} = p_{\text{in}}$
- for example
  - evaporator: $h_{\text{out}} = h_{\text{sat,gas}}\left(p\right)$
  - condenser: $h_{\text{out}} = h_{\text{sat,liq}}\left(p\right)$
- two-sided
  - $\dot{Q}_{\text{h}} = \dot{m}_{\text{h}} \cdot (h_{\text{out,h}} - h_{\text{in,h}})$
  - $\dot{Q}_{\text{c}} = -\dot{Q}_{\text{h}} = \dot{m}_{\text{c}} \cdot (h_{\text{out,c}} - h_{\text{in,c}})$

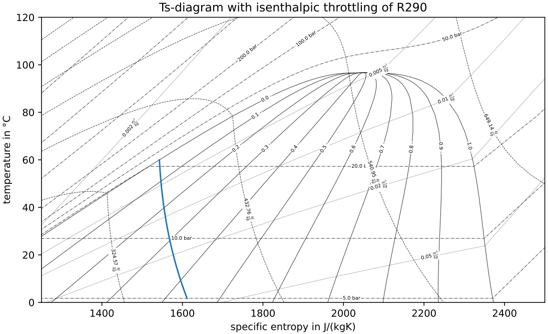




Components: Valve

Components: Valve

- adiabatic and no transfer of work
  - $\dot{W} = 0$
  - $\dot{Q} = 0$
- energy balance: $0 = \dot{m} \cdot (h_{\text{out}} - h_{\text{in}})$
- pressure ratio: $pr = \frac{p_{\text{out}}}{p_{\text{in}}} < 1$



Exercise

Implement a model, that allows you to model isentropic compression.

- What power does the compressor draw if 5 kg/s of R290 are compressed from saturated gaseous state at 15 °C to a pressure corresponding to a saturation temperature of 60 °C?
- What is the outlet temperature?
- How much mass can be compressed by the same machine, if 300 kW of power is available?

Now consider thermodynamic inefficiencies by incorporating isentropic efficiency in the model.

- How does the compressor power requirement change as function of the isentropic efficiency? The starting point is the same as in the first assignment.
- The outlet temperature is measured to be 80 °C, what is the isentropic efficiency?

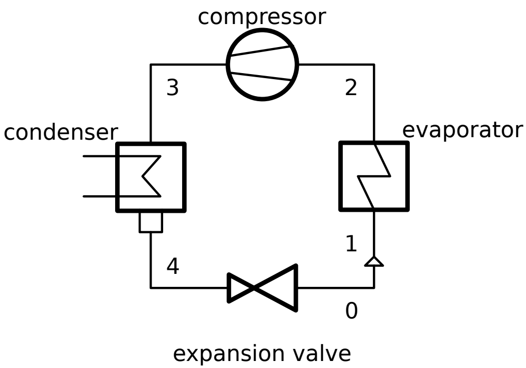
Exercise

- With R290 as working fluid, assume the compressor power is limited to 0.2 MW:
  - How much heat can be provided by the condenser in this case?
  - What is the maximum temperature the condenser can deliver, if it should still provide 1 MW of heat?

Simple heat pump model

Simple heat pump model

- Simple 4-component cycle
- No secondary side for heat exchangers



Model	parameters		
location	parameter	value	unit
2	temperature	10	°C
4	temperature	60	°C
compressor	efficiency	80	%
condenser	heat transfer	1	MW

Exercise

- Create a model of the heat pump using R290 as refrigerant in Python and calculate
  - the compressor power input
  - the COP of the heat pump
  - the mass flow of the refrigerant
  - the evaporation and the condensation pressure levels
- Create a log p-h diagram of the process
- Change the working fluid to ammonia. Why and how does it affect the COP?
- Create two plots, that indicate dependency of the COP towards evaporation and condensation temperature respectively?

Exercise

- With R290 as working fluid, assume the compressor power is limited to 0.2 MW:
  – How much heat can be provided by the condenser in this case?
  – What is the maximum temperature the condenser can deliver, if it should still provide 1 MW of heat?

Let's code it!